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Optoelectronic Workshops: Liquid Crystals for Laser Applications

12. PERSONAL AUTHOR(S)
Stephen Jacobs, University of Rochester; and Juergen Pohlmann, NVEOC

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17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This optoelectronic workshop represents the fourth of a series of intensive academic/ government interactions in the field of advanced electro-optics as part of the Army sponsored University Research Initiative. The workshops are a collaboration between the Center for Opto-Electronic Systems Research at the University of Rochster, Rochester, New York and the U.S. Army Center for Night Vision and Electro-Optics, Ft. Belvoir, Virginia. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO-URI) and Dr. Rudy Buser, NVEOC.

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The Center for Night Vision and Electro-Optics

OPTOELECTRONIC WORKSHOPS

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IV

LIQUID CRYSTALS FOR LASER APPLICATIONS

May 11, 1988

sponsored jointly by

ARO-URI Center for Opto-Electronic Systems Research
The Institute of Optics, University of Rochester

OPTOELECTRONIC WORKSHOP

ON

LIQUID CRYSTALS FOR LASER APPLICATIONS

Organizer: ARO-URI-University of Rochester
and Center for Night Vision and Electro-Optics

1. INTRODUCTION

2. SUMMARY -- *INCLUDING FOLLOW-UP*

3. VIEWGRAPH PRESENTATIONS

   A. Center for Opto-Electronic Systems Research
      Organizer -- Stephen Jacobs

      A Dozen Liquid Crystal Device Concepts
      Stephen Jacobs

      Nonlinear Optics and Laser Damage Resistance
      of Liquid Crystals
      Ansgar Schmid

      Ferroelectric Liquid Crystals
      Kenneth Marshall

   B. Center for Night Vision and Electro-Optics
      Organizer -- Juergen Pohlmann

      Historical Perspective: Liquid Crystal Research
      at Fort Belvoir
      Wolfgang Elser

      Current Liquid Crystal Research
      Juergen Pohlmann

      Liquid Crystal Electro-Optic Shutter
      James Miller

4. LIST OF REFERENCES

5. LIST OF ATTENDEES

6. DISTRIBUTION

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1. INTRODUCTION

This workshop represents the fourth of a series of intensive academic/ government interactions in the field of advanced electro-optics, as part of the Army sponsored University Research Initiative. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO-URI) and Dr. Rudy Buser, NVEOC.

2. SUMMARY AND FOLLOW-UP ACTIONS

a. IR Light Scatterer:

Based upon viewgraphs provided by J. Miller and subsequent discussions, we will consider liquid crystal and other technologies which might have the required performance. We will discuss our concepts further with him to define, if possible some activity which we might jointly pursue (within our resource base) to construct and characterize an alternative device concept.

b. Optical Power Limiter:

Perhaps Night Vision and Electro-Optic Center wants to organize a more narrowly defined meeting to address their specific needs compared to objectives already being pursued by the NADC and the BAA. We would be happy to help organize and participate in such a meeting.

c. Holographic Photopolymer:

We will obtain more information from Dr. Thomas Stone (U of R) to see if there is some input we can make to the doping of liquid crystals into porous polymer films. Mark Norton (NV&EOC) has an interest in this.

CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH

A DOZEN LIQUID CRYSTAL DEVICE CONCEPTS

A Dozen Liquid-Crystal Device Concepts

UR
LLE

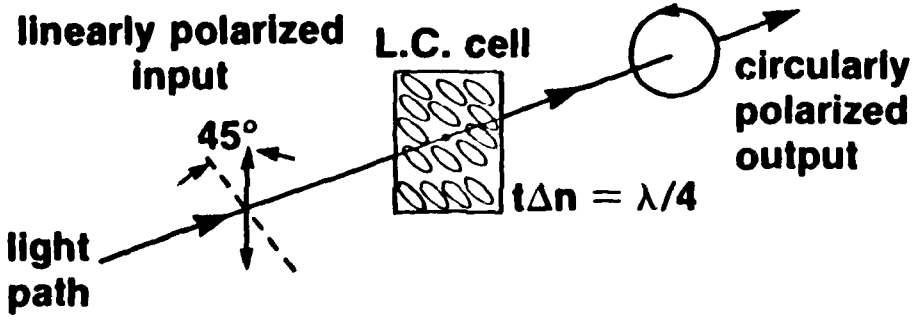
(1) Wave Plate
(2) Polarizer
(3) Isolator
(4) Beam Splitter
(5) Mirror
(6) Notch Filter
(7) Attenuator
(8) Beam Apodizer
(9) (Bistable) Beam Deflector
(10) Shutter/Chopper
(11) Power Limiter
(12) Light Scatterer

G2299

Nematic Class: Device Application
True Zero-Order Wave Plates

UR LLE

Quarter Wave Plate

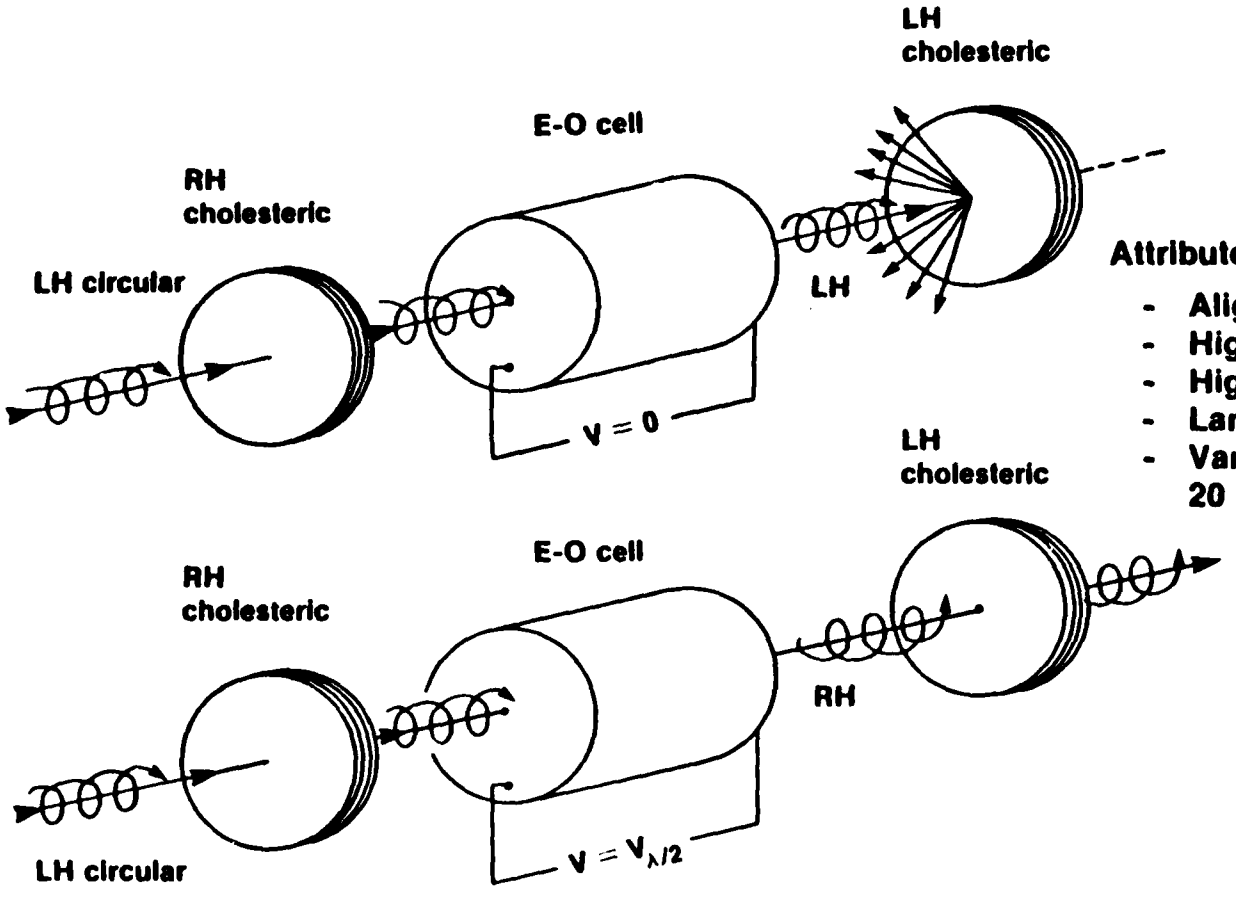


Properties of Interest	Liquid Crystals	MgF^2 Mica Quartz Sapphire Plastics
• Spectral transmission	UV-IR	
• Refractive index	1.45-1.80	
• Birefringence	0.035-0.280	
• Thickness for λ/2 plate	1-4 μm	
• Accuracy of retardance	±1% with blending	
• Uniformity of retardance	±1.5 nm across 100 mm	
• Angular sensitivity	weak	
• Laser-damage resistance	>6 J/cm^2 (1 ns, 1000 nm)	
• Optical quality	substrate defined	
• Aperture limits	none	

G2300

Circular Polarizer for Pockels' Cell, E-O Switching

UR
LLE



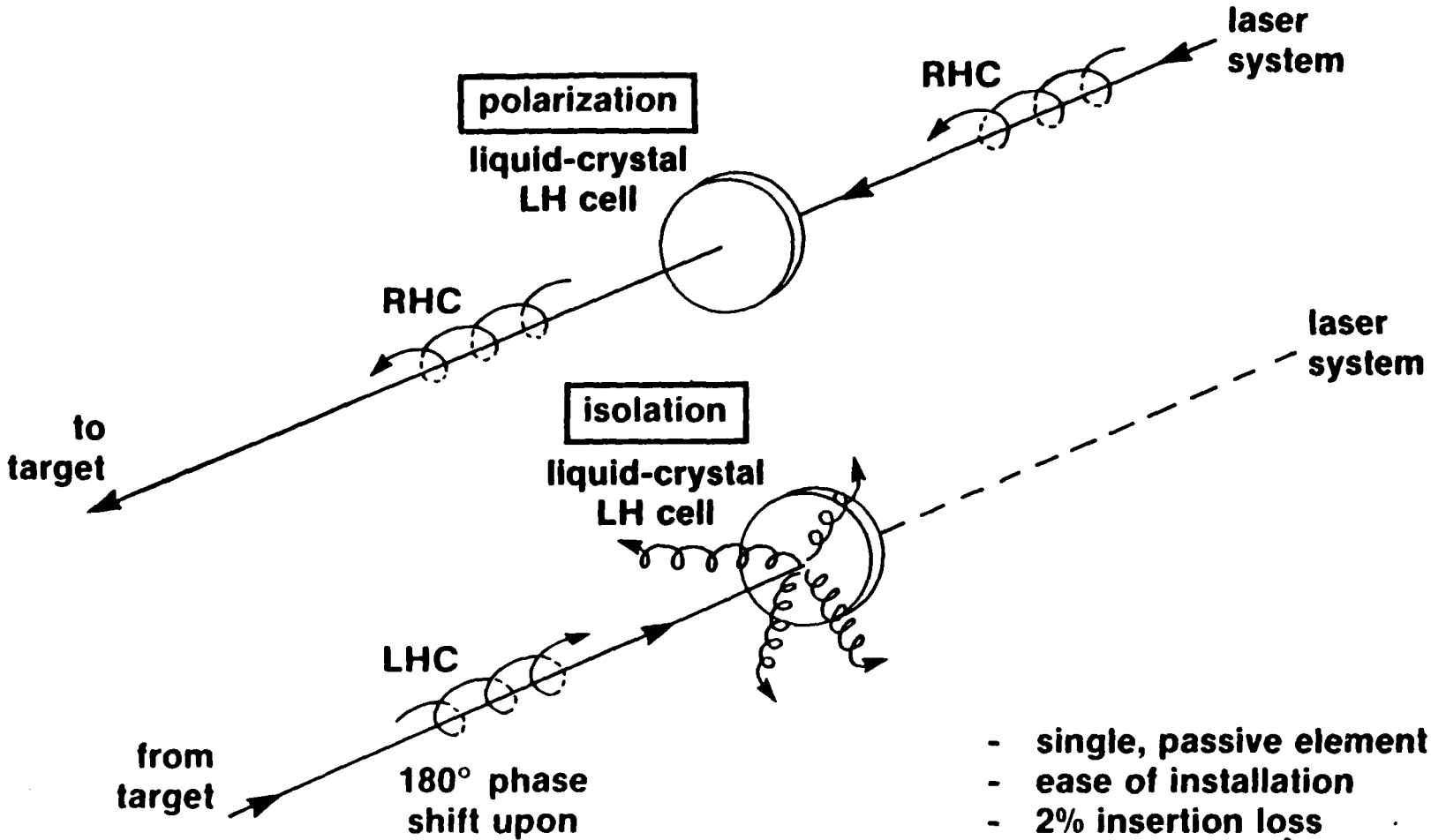
Attributes

- Alignment insensitivity, ±10°
- High contrast on/off, 10^4 O.D.
- High transmission, 98%
- Large aperture
- Variable bandwidth, 20 nm to 200 nm

G1392

Dual Role for Liquid-Crystal Polarizers: Polarization and Isolation

UR LLE

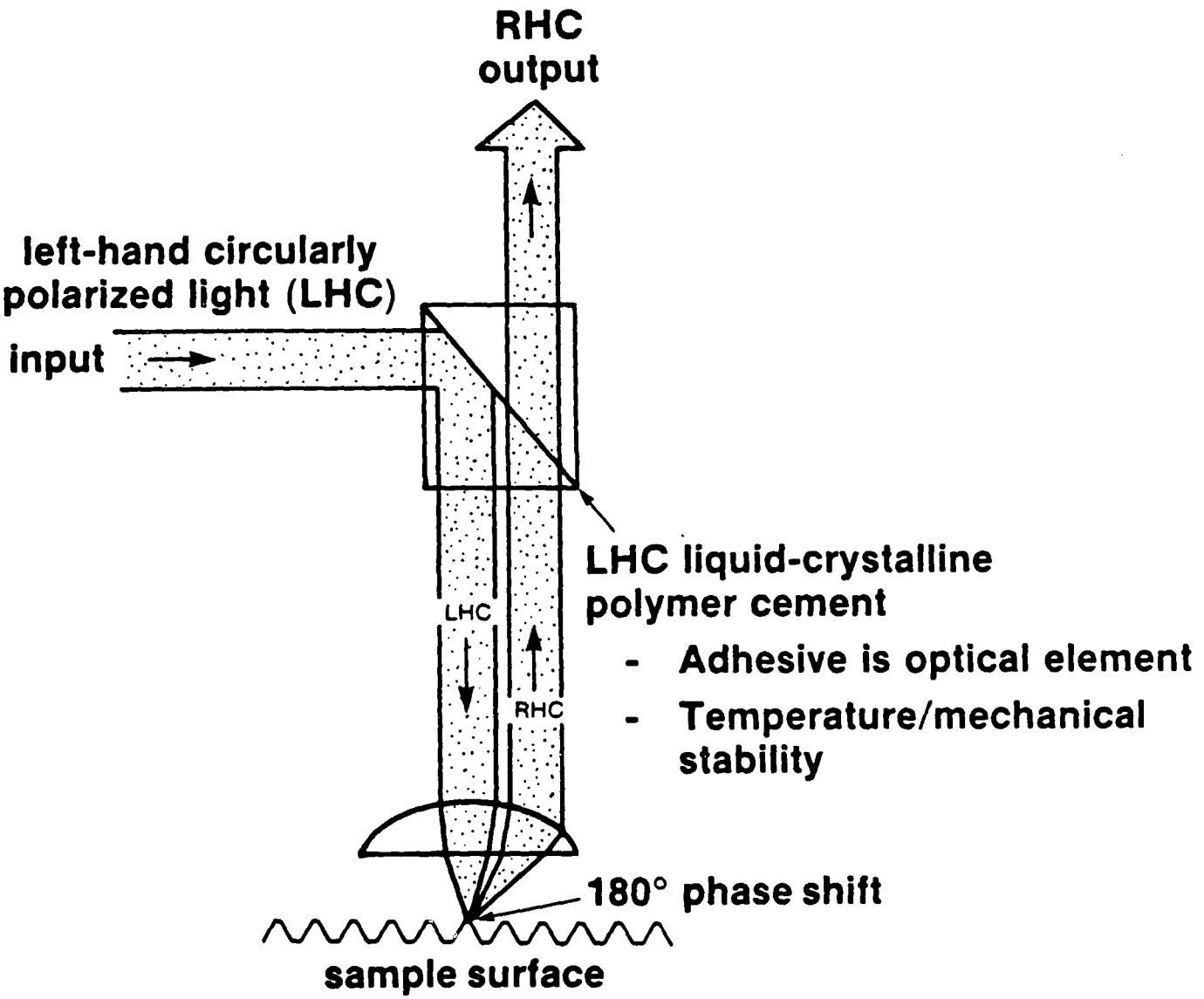


- single, passive element
- ease of installation
- 2% insertion loss
- isolation to 10^4:1

G2155

Beam-Splitter Liquid-Crystal-Polarizing Prism

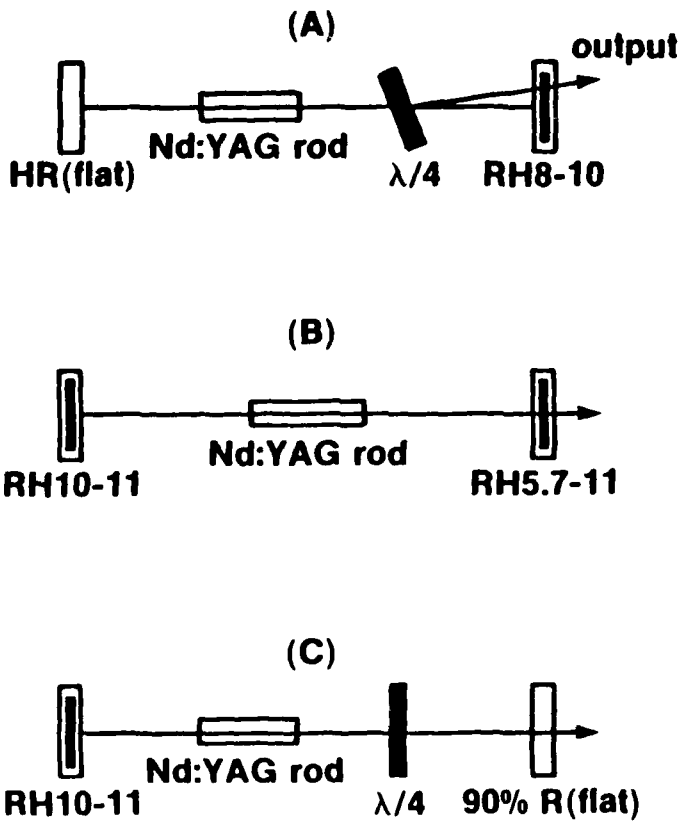
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G2301

Liquid-Crystal Mirror
Laser Resonator Configuration

UR LLE

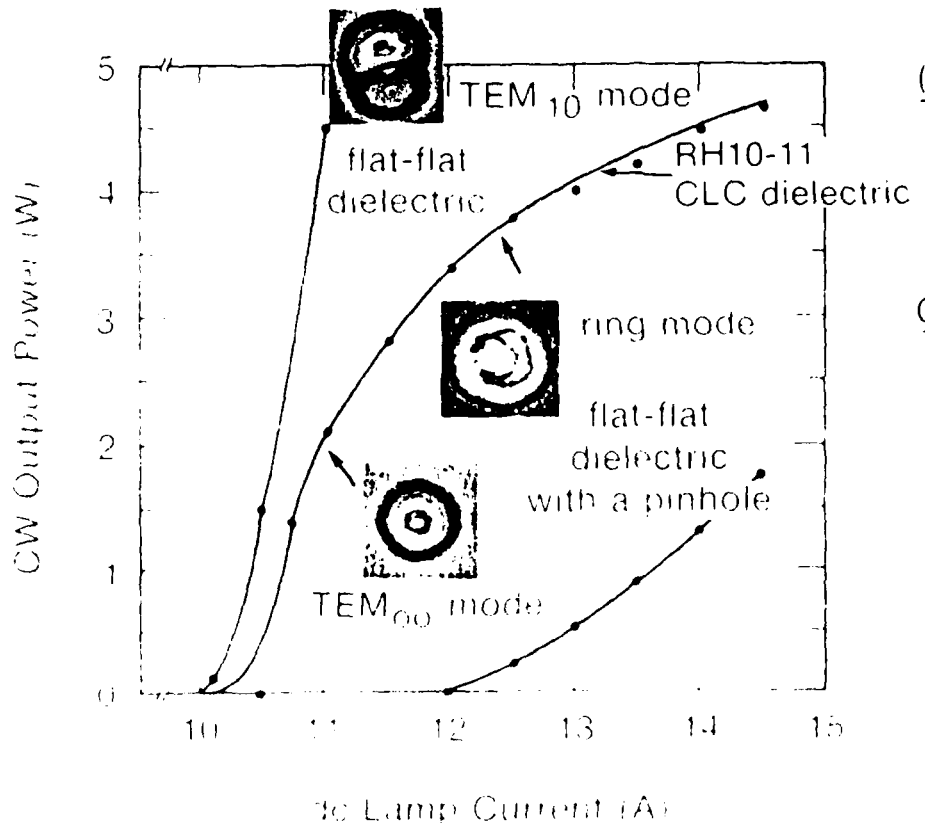


- Modification to a Control Laser Corp. model 256 Nd:YAG head (cw)
  - (A) CLC (thick)-dielectric: output via Fresnel reflection
  - (B) CLC (thick)-CLC (thin): output though thin partial reflector demonstrated
  - (C) CLC (thick)-dielectric: output through 90% R
- Performance improvements
  - TEM_{oo} output without pinhole
  - Reduced angular sensitivity

G2302

Comparison of CLC Resonator with Dielectric Resonator

UR LLE



(flat-flat) dielectric resonator

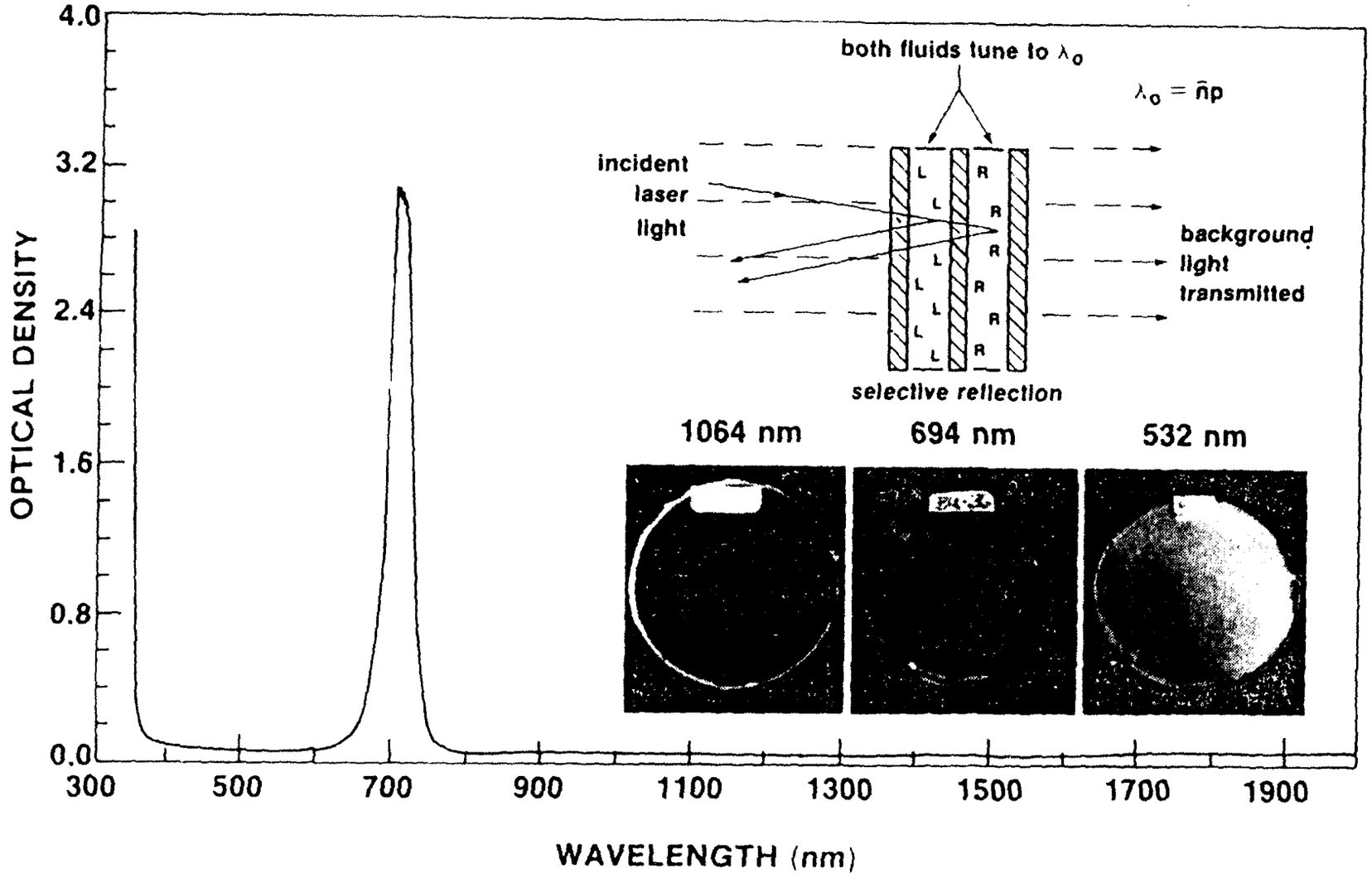
- multimode output profile with no internal aperture
- high sensitivity to mirror tilt (± 0.8 arcsec)

CLC-dielectric resonator

- TEM_{00} mode operation with no internal aperture
- low sensitivity to mirror tilt (± 1.8 arcsec)

LIQUID-CRYSTAL LASER-BLOCKING FILTER

UR
LLE



G1482

Optical Radiation Attenuator

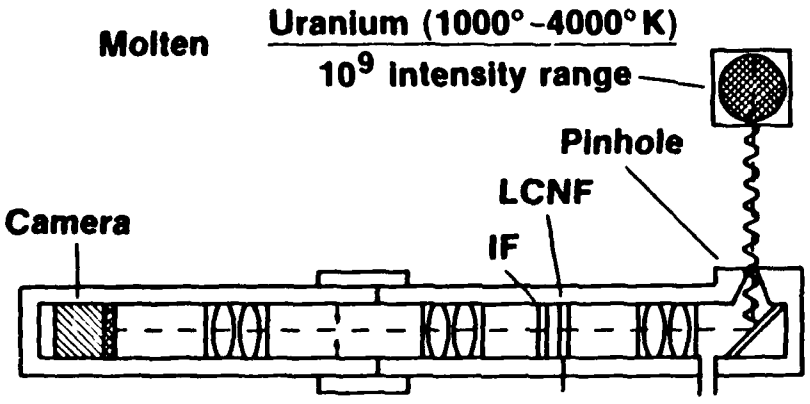
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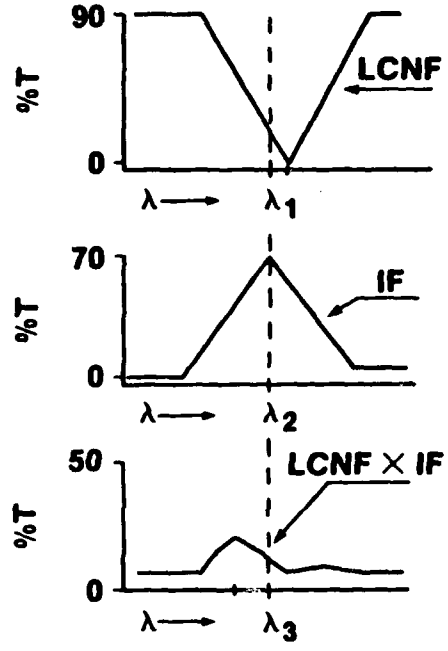
United States Patent [19]
Rushford

[11] **Patent Number: 4,726,660**
[45] **Date of Patent: Feb. 23, 1988**

[54] **TECHNIQUE FOR COMPRESSING LIGHT INTENSITY RANGES UTILIZING A SPECIFICALLY DESIGNED LIQUID-CRYSTAL *NOTCH FILTER***

[75] **Inventor: Michael C. Rushford, Livermore, CA**

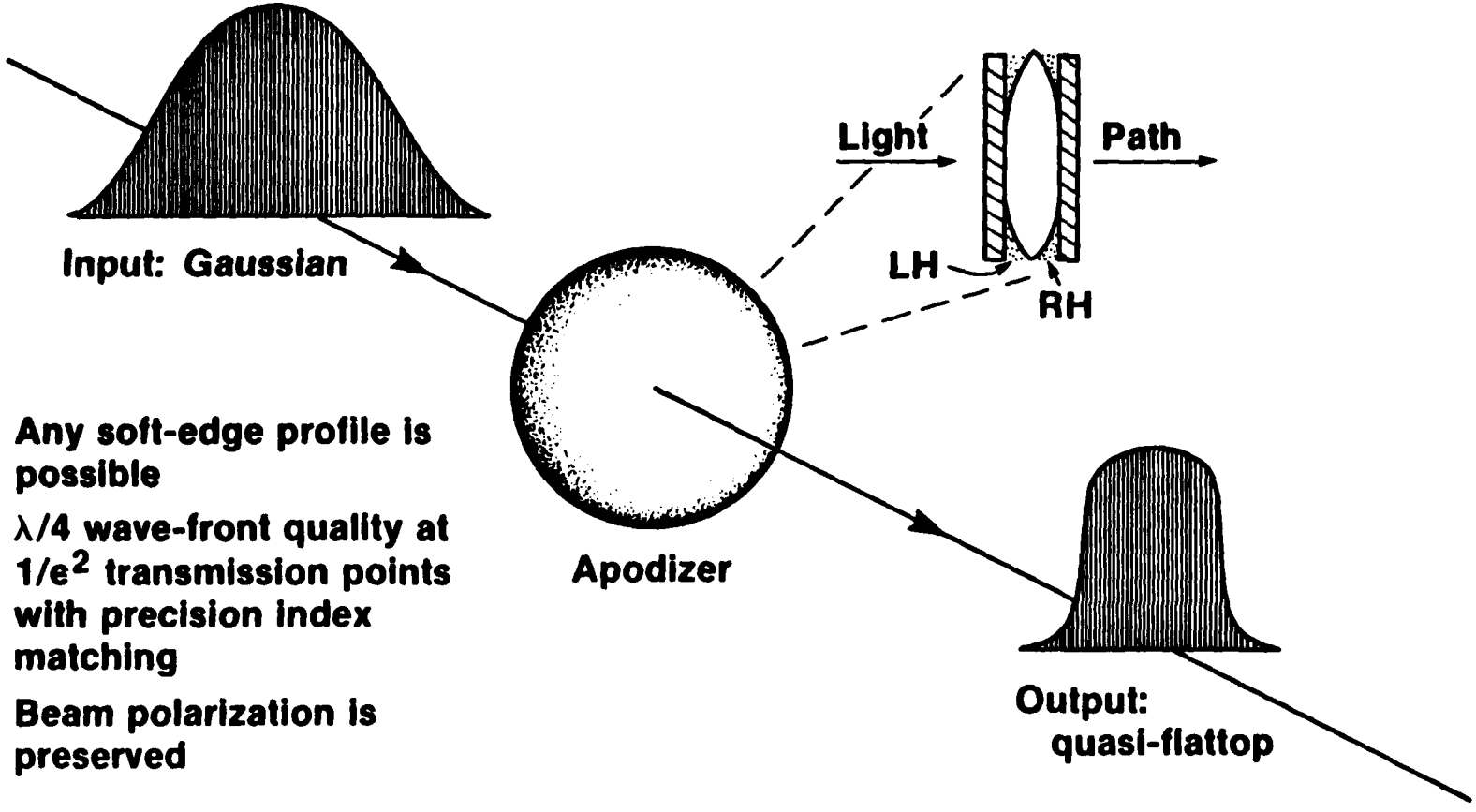




G2303

Liquid-Crystal Laser Beam Apodizers

UR LLE

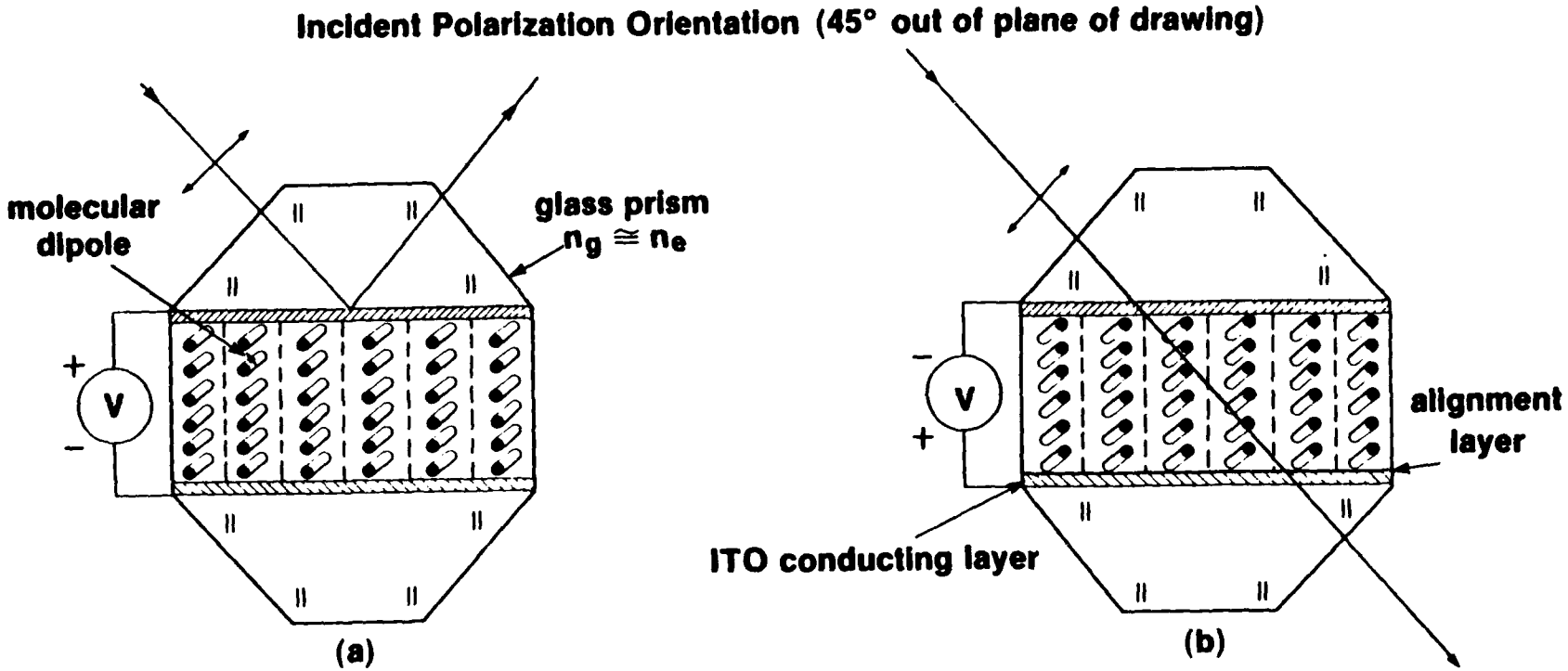


- Any soft-edge profile is possible
- $\lambda/4$ wave-front quality at $1/e^2$ transmission points with precision index matching
- Beam polarization is preserved

G2304

Two-Position Bistable Beam Deflection Device Using fTIR in Ferroelectric Chiral Smectic C Mesogens

UR LLE



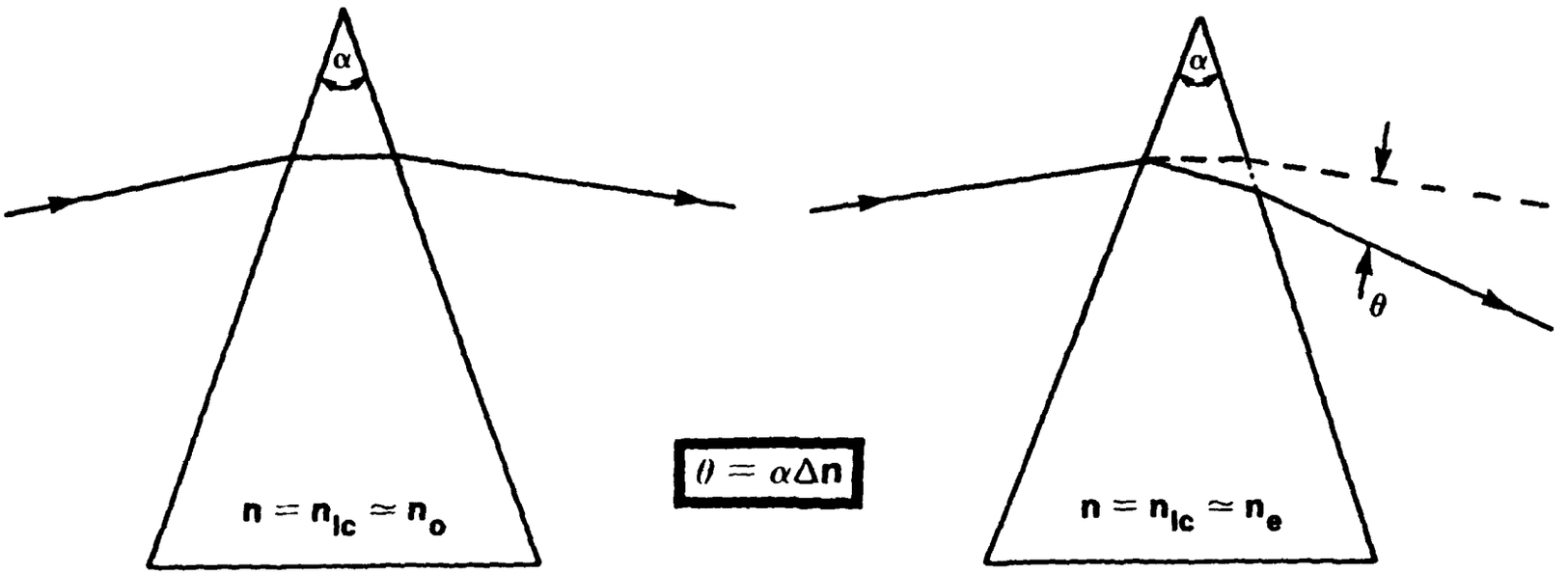
(a) Incident radiation experiences n_o, allowing TIR. (b) Reversal of field polarity causes incident radiation to experience n_e, resulting in fTIR.

G1953

Liquid-Crystal Wedge Multiposition Beam Deflector Concept

UR LLE

- Several possible modes of operation
  - bistable
  - bistable with tunable birefringence around two bistable positions
  - nonbistable



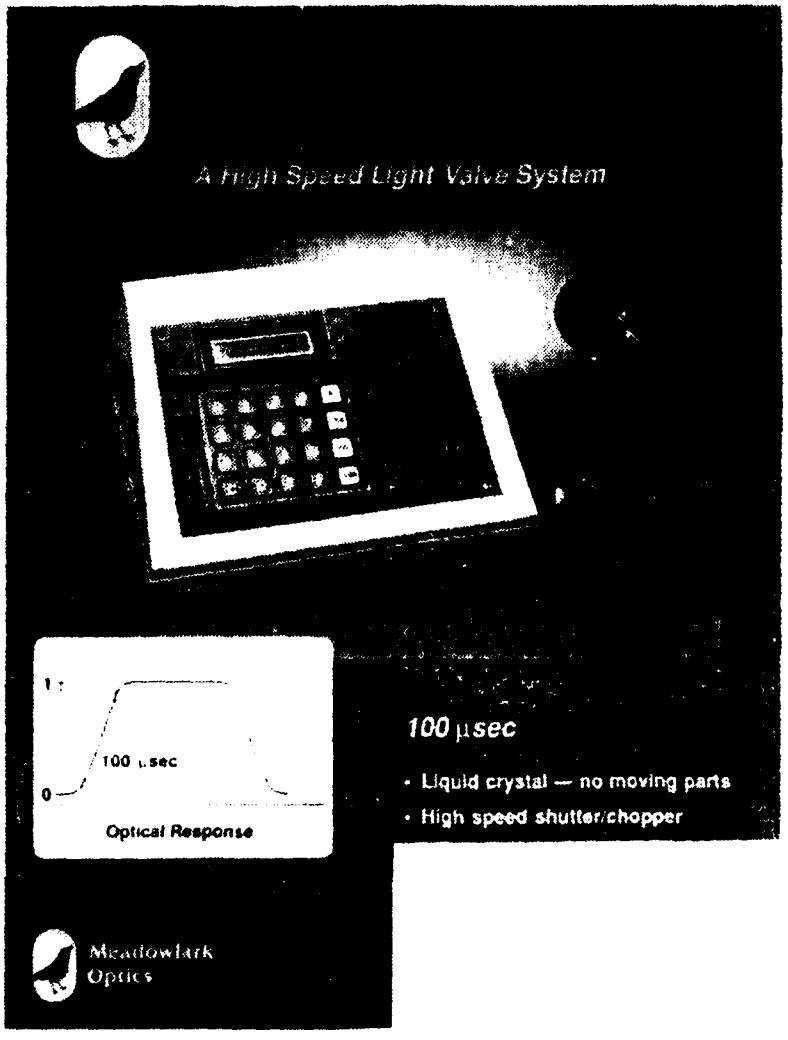
$$\theta = \alpha \Delta n$$

where θ = deflection angle (several tenths of a degree)
α = cell wedge angle (0.1–1.0 degrees)
Δn = change in refractive index due to field-induced director reorientation (as large as 0.2)

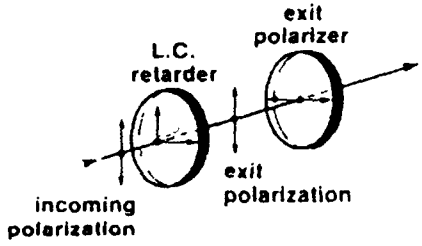
G2305

Ferroelectric Liquid-Crystal Shutter/Chopper

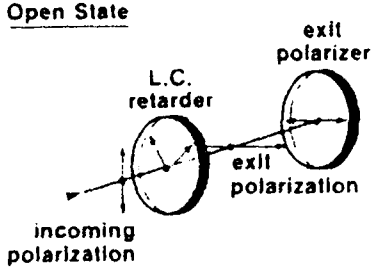
UR
LLE



Closed State



Open State

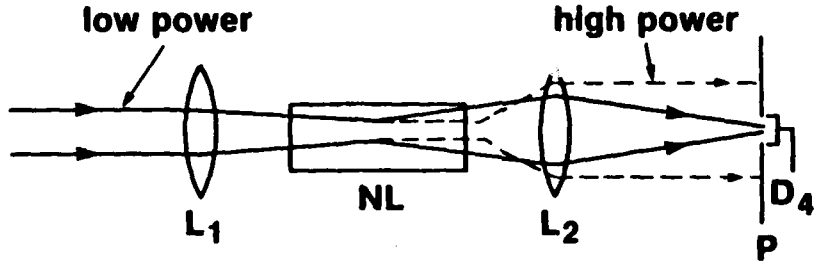


G2306

Optical Power Limiter Geometries

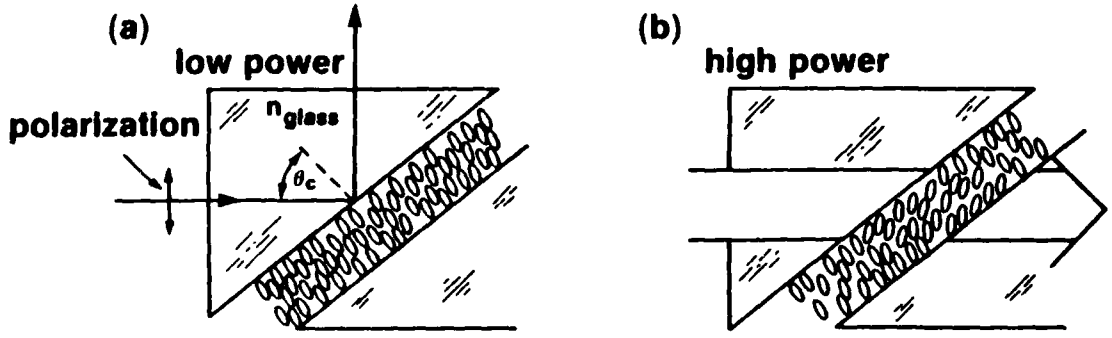
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- **Self Focusing**



- After Solleau *et al., IEEE J. Quantum Electron.* QE-19, 731 (1983).

- **Total Internal Reflection**



G2307

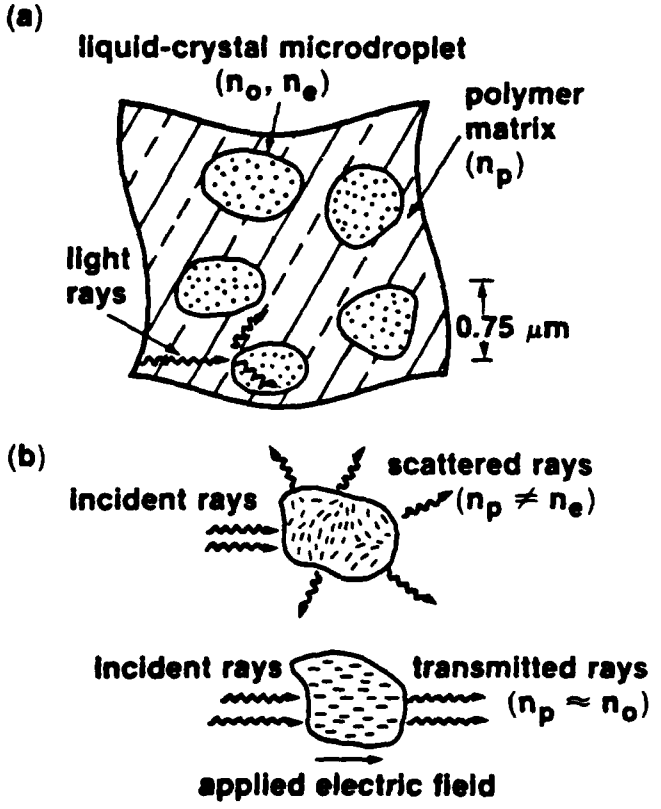
Polymer-Dispersed Liquid Crystals Induced Light Scattering

United States Patent [19]
Fergason

[11] Patent Number: 4,556,289
[45] Date of Patent: Dec. 3, 1985

[54] LOW BIREFRINGENCE ENCAPSULATED LIQUID CRYSTAL AND OPTICAL SHUTTER USING SAME

[75] Inventor: James L. Fergason, Kent, OH



From N. A. Vaz and G. P. Montgomery, Jr., *J. Appl. Phys.* 62, 3161 (1987).

CLEO
TUESDAY, 26 APRIL 1988
Anaheim Convention Center

TuT, Light Manipulation with New Materials
4:30 PM
TuT1 Observation of Optical Limiting Using Polymer-Dispersed Liquid-Crystal Thin Films,
David M. Pepper, J. David Margerum, Anna M. Lackner, Elena Ramos, *Hughes Research Laboratories.* Optical limiting using polymer-dispersed liquid crystals is demonstrated. These heterogeneous mixtures are index matched at low intensities, and behave as diffuse scatterers in the nonlinear regime due to optical reorientation of the liquid-crystal dispersant.

CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH

NONLINEAR OPTICS AND LASER DAMAGE RESISTANCE OF LIQUID CRYSTALS

Two Dominant Physical Mechanisms for Third-Order Optical Nonlinearities in Liquid Crystals

UR LLE

- **Orientational**

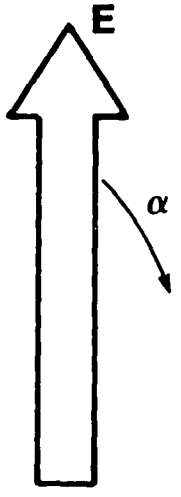
  based on large birefringence: $\Delta n = 0.1\text{–}0.2$

- **Electronic**

  based on electron delocalization

G2309

Linearly polarized external field induces torque



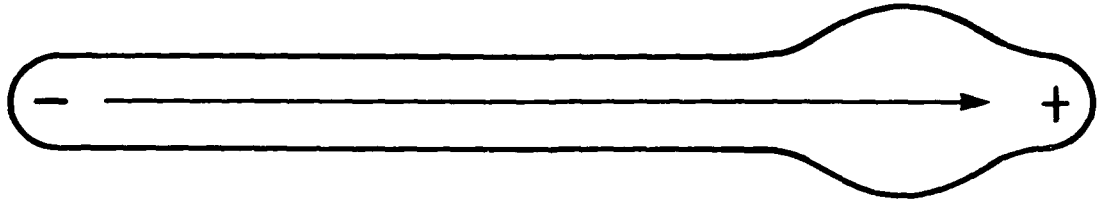
Result: Field-driven molecular reorientation (Freedericksz effect)

G2312

Mechanism of Orientational Optical Nonlinearity in Liquid Crystals

UR
LLE

Donor/acceptor (substituent) pairs on liquid-crystal core introduce electric dipole moment



G2311

The Dynamics of the Freedericksz Transition Is Driven by the External Forces and Elastic Restoring Forces

UR LLE

- **Free energy density:**

$$F = \int_V d^3r \, \frac{1}{2} \left\{ \kappa_{11} (\nabla \cdot \vec{n})^2 + \kappa_{22} [\vec{n} \cdot (\nabla \times \vec{n})] + \kappa_{33} (\vec{n} \times \nabla \times \vec{n})^2 \right.$$

elastic part

$$+ (\vec{E} \cdot \vec{D} + \vec{B} \cdot \vec{H})$$

electromagnetic part

- **Maxwell:**

$$\vec{D} = \epsilon(\alpha) \, \vec{E}$$

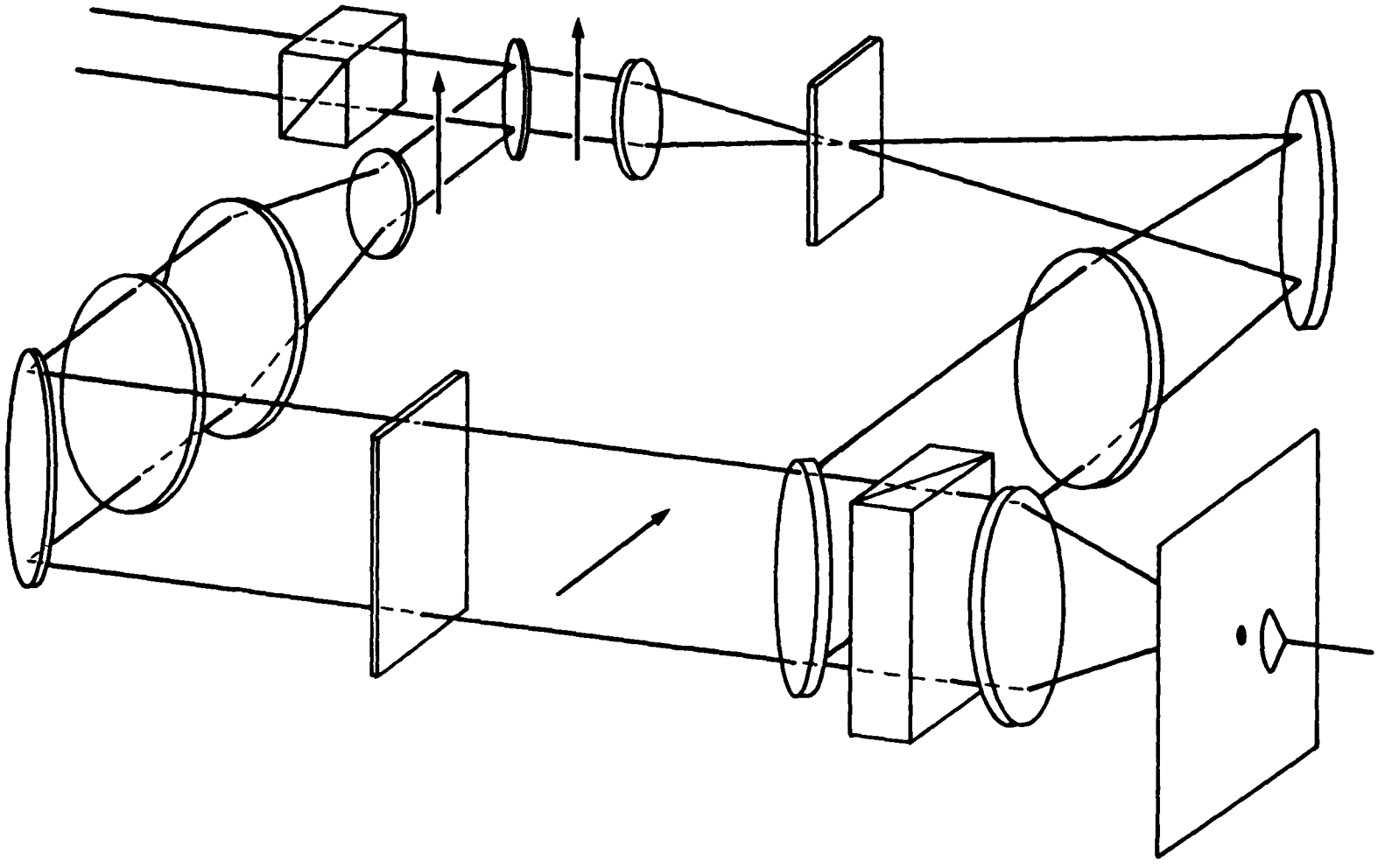
- **Euler-Lagrange:**

$$\delta^2_{xx} \, \alpha + \delta^2_{zz} \, \alpha + A \frac{\sin\alpha \cos\alpha}{(1\text{-}B \sin^2 \alpha)^{3/2}} = 0$$

G2314

Mach-Zehnder Interferometer for Self-Phase-Modulation Measurements in Thin Liquid-Crystal Cells

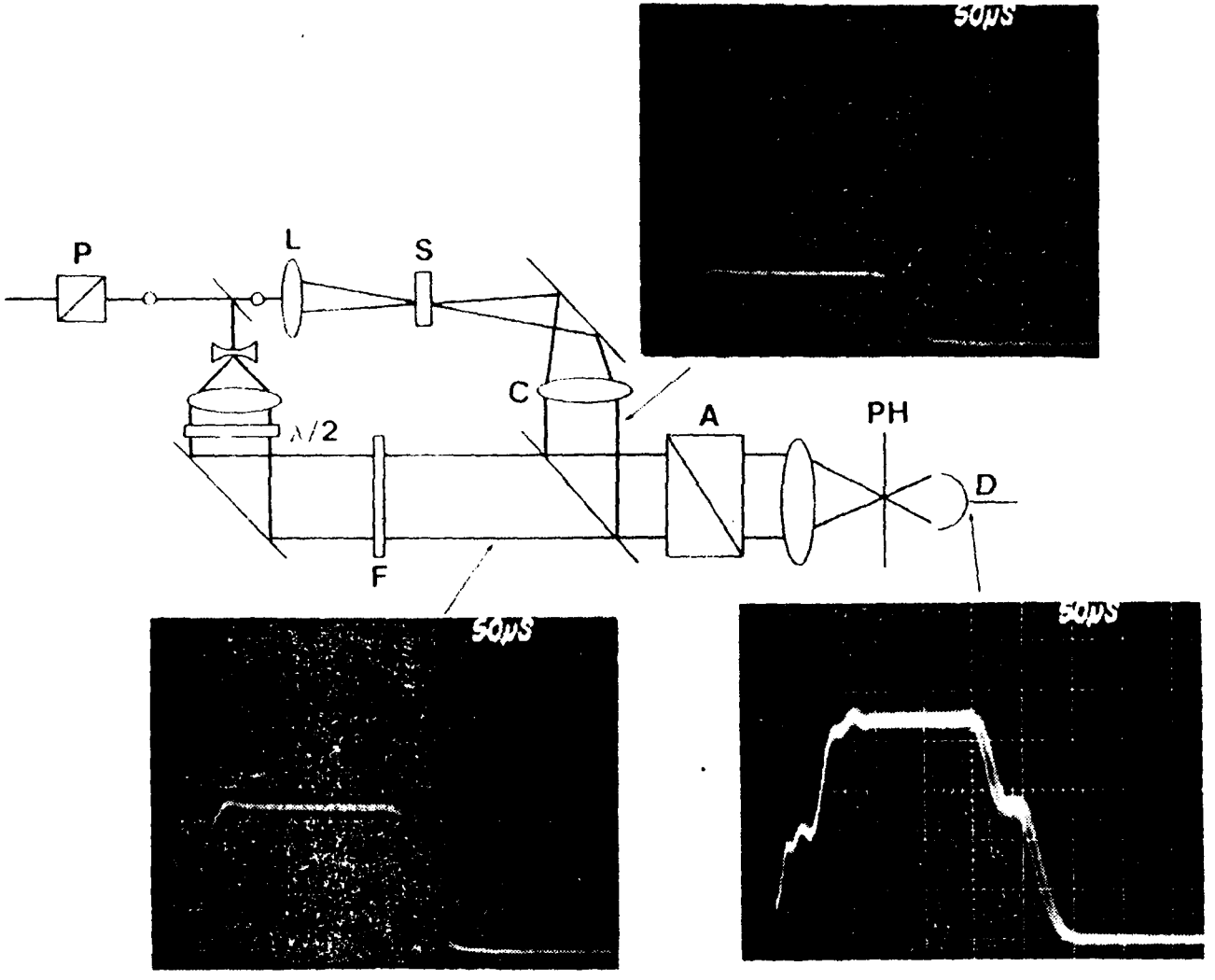
UR LLE



G2317

Temporal Self-Phase Modulation in Nematic, Smectic-A Octyl-Cyanobiphenyl

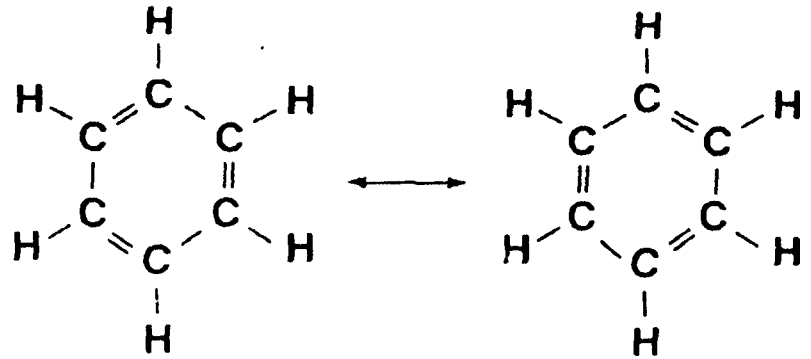
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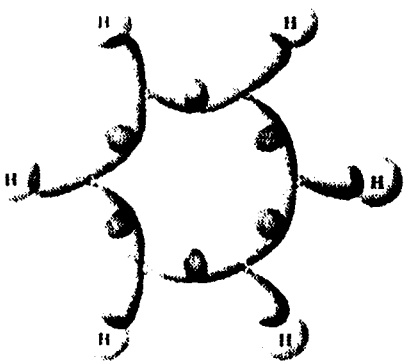


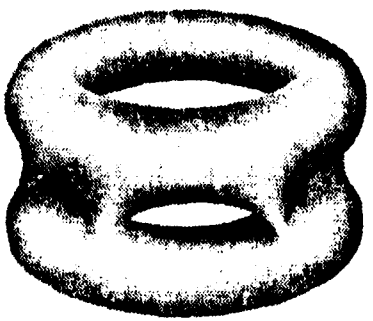
G2318

Delocalized Orbitals in Aromatic Systems

UR
LLE







δ
Bonded

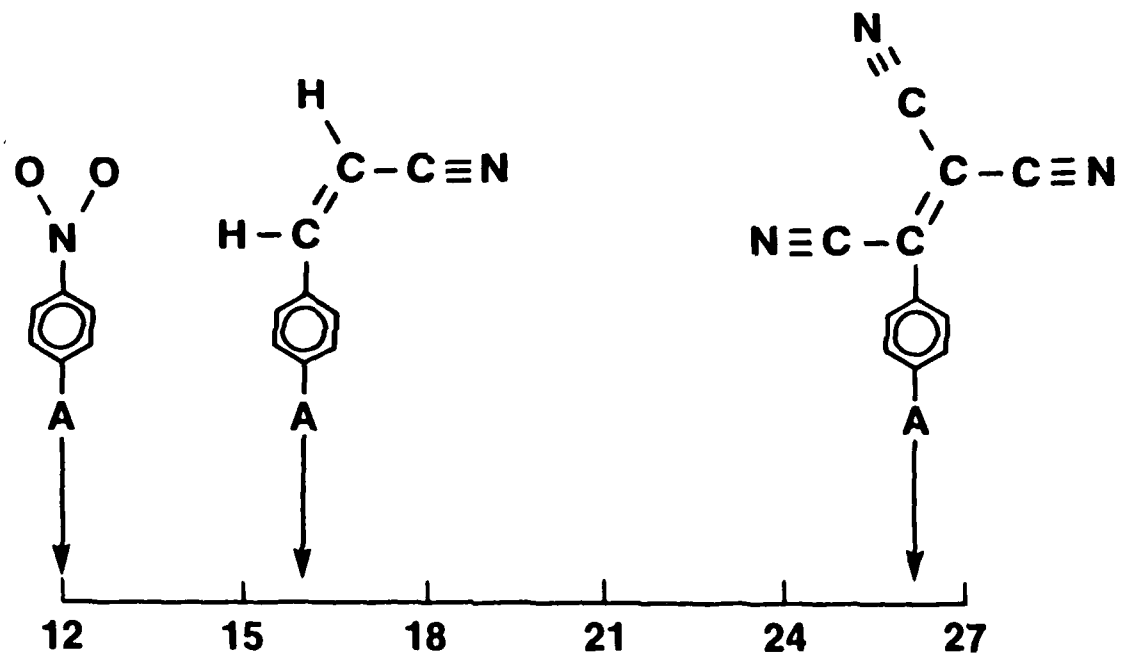
π
Bonded

Electronic Molecular Hyperpolarizability Is Strongly Enhanced by π-Electron Delocalization

UR LLE

Second-Order Example:

frequency conversion at 1.3 μm
(AT&T Bell Laboratories)



G2313

We Demonstrate The Link Between 1053-nm Laser Damage and Degree of Conjugation in Liquid Crystals

UR LLE

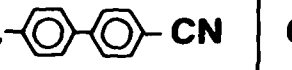
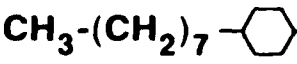
- Use both monomeric and polymeric systems
- Prepare samples of identical pathlength ($\sim$ 100 μm)
- Monitor impurity trace levels
- Limit use of alignment layers
- Test at identical wavelength and pulse length

G2315

Fully Saturated Electron System Raises 1053-nm Damage Threshold in Liquid Crystals

UR LLE

Damage Threshold Comparison of Two Model Compounds
(800-ps pulse length, 100-μm path length, 5-mm spot size, linear polarization)

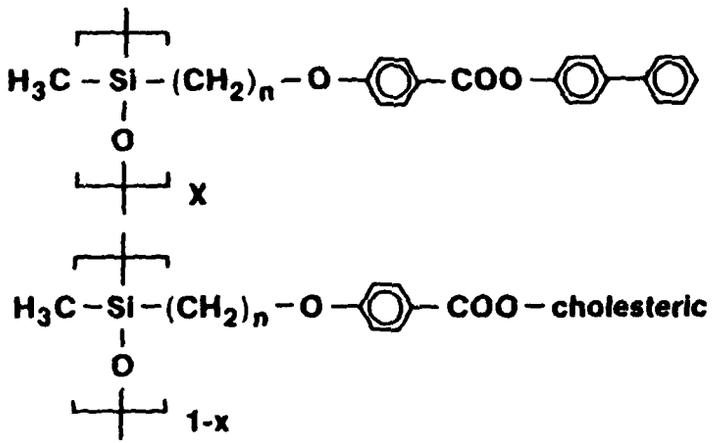
Compound	K-15	ZLI-1185
Structure		
Mesophase	nematic (22°C)	nematic (62°C)
1-on-1 (J/cm^2)	9.6±2.4	>16.6*
N-on-1 (J/cm^2)	5.4±1.3	14.6±0.5

- Liquid crystals unaligned; alignment layers usually lower threshold

*for given spot size, transport optics damage at 20 J/cm^2

G2247

Reduced Conjugation Volume Density Improves Laser Damage Threshold In Chiral Nematic Polymer



Weight % Cholesteric	Tuned Peak Wavelength (nm)	Film Thickness (μm)	1-on-1 Threshold (J/cm^2) at 1054 μm/1 ns
14	1170	108	0.8±0.1
21	760	104	2.2±0.4
35	450	84	5.1±1.2

G2316

Summary

UR
LLE

- Large, moderate-speed optical nonlinearities available through Freedericksz reorientation in liquid crystals
- When laser damage is a potential problem, choose organic materials that are highly saturated (free of conjugated bonds)
- There may be trade-offs between high damage threshold and other optical, mechanical or thermal properties
- Measured damage thresholds compare well with those of standard coatings

G2321

CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH
FERROELECTRIC LIQUID CRYSTALS

Presentation Format

UR
LLE

- Background-dielectric E-O effects in nematic liquid crystals
- Origin of ferroelectric E-O effects in chiral smectic liquid crystals
- Current status of ferroelectric liquid-crystal device technology
- Materials considerations for ferroelectric liquid-crystal devices

Electro-Optic Devices Based on Dielectric Effects in *Nematic* Liquid Crystals

UR LLE

- Wide application in information display area
  - low operating voltage
  - low power consumption
  - relatively easy to fabricate
  - good contrast in strong ambient lighting
- Disadvantages for high-speed optical processing/switching applications
  - slow response times (10–500 ms)
  - static electric field required to reorient and stabilize director (not bistable)
  - electro-optic response *not* field linear (strong threshold effect)

G1926

Ferroelectric Liquid Crystals
Advantages

UR
LLE

- Fast response - 0.5 μs demonstrated, nanosecond response times predicted
- Bistable switching effect - pulsed dc drive
- Optic axis orientation determined by polarity of applied electric field
- Field-linear E-O response possible under certain conditions
- Large E-O response for thin cell spacings

G2319

Classification of Ferroelectric Smectic Phases

UR
LLE

GROUP I: Smectic Liquid Crystals (C^*, I^*, F^*)

- No long-range periodic ordering
- Smectic C^*: random ordering within layer
- Smectic I^* and F^*: hexagonal close packed within layer

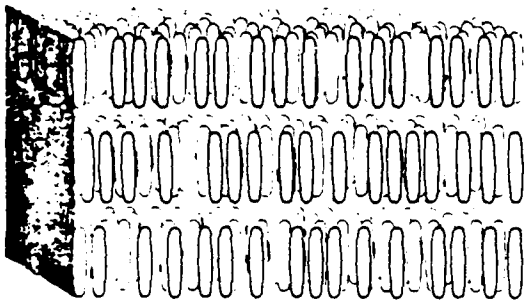
GROUP II: Anisotropic plastic crystals (J^*, G^*, K^*, and H^*)

- Long-range ordering of molecules in three dimensions

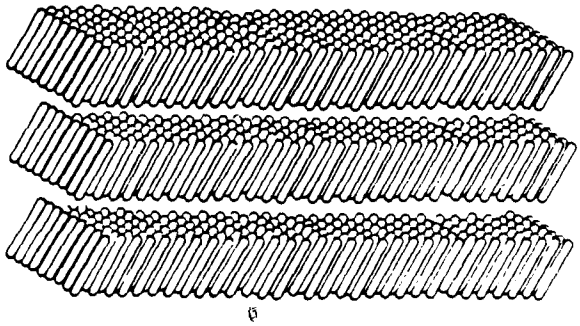
G1930

Structures in Smectic Class

UR LLE

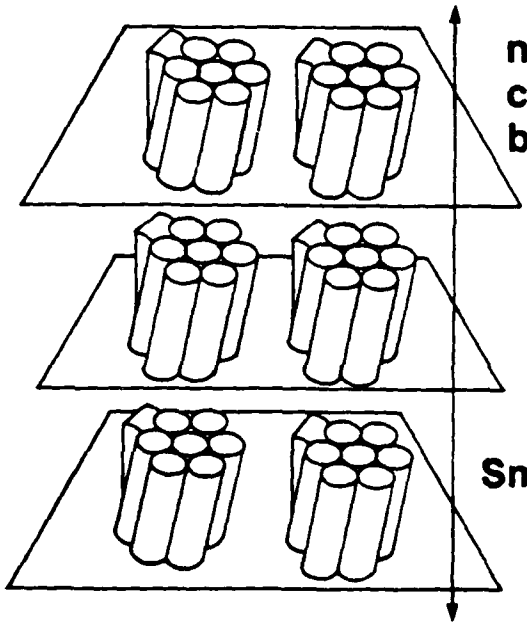


Smectic A



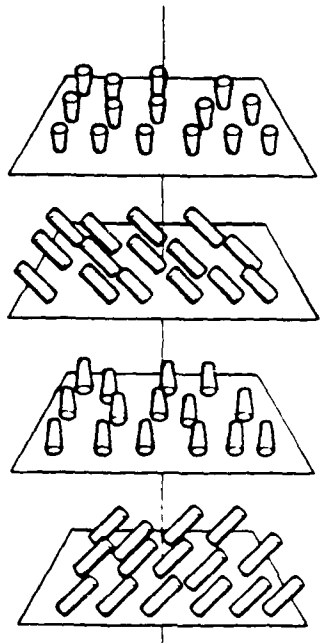
Smectic C

short-range
hexagonal order



no long-range
correlations
between layers

Smectics I and F



Chiral Smectic C

G1931

Origin of Ferroelectric Effects in Chiral Smectic Liquid Crystals

UR LLE

Ferroelectric Materials: defined as materials that over a certain temperature range possess a spontaneous polarization (or net dipole moment per unit volume), which is reversible by an external electric field

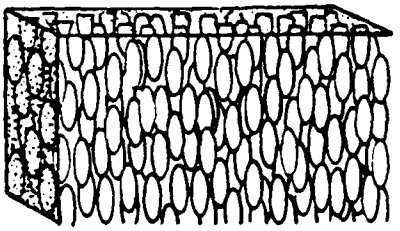
Dipolar ordering can arise in any system having a layered structure, tilt, and chirality of its constituent molecules (R. B. Meyer, Harvard University, 1975)

Chiral smectic liquid crystals fulfill these requirements.

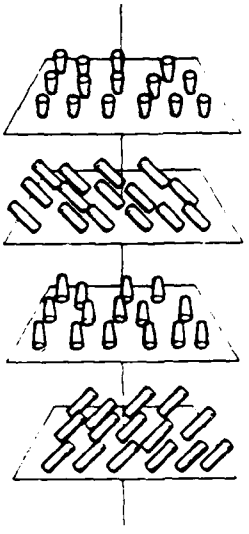
G1927

Diagram 1

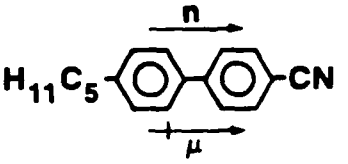
UR
LLE



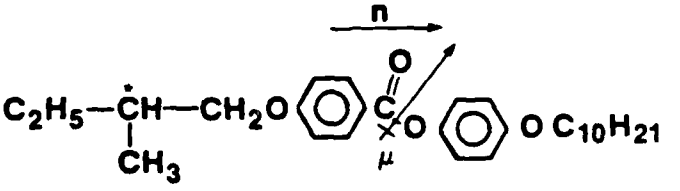
(a)



(c)



(b)

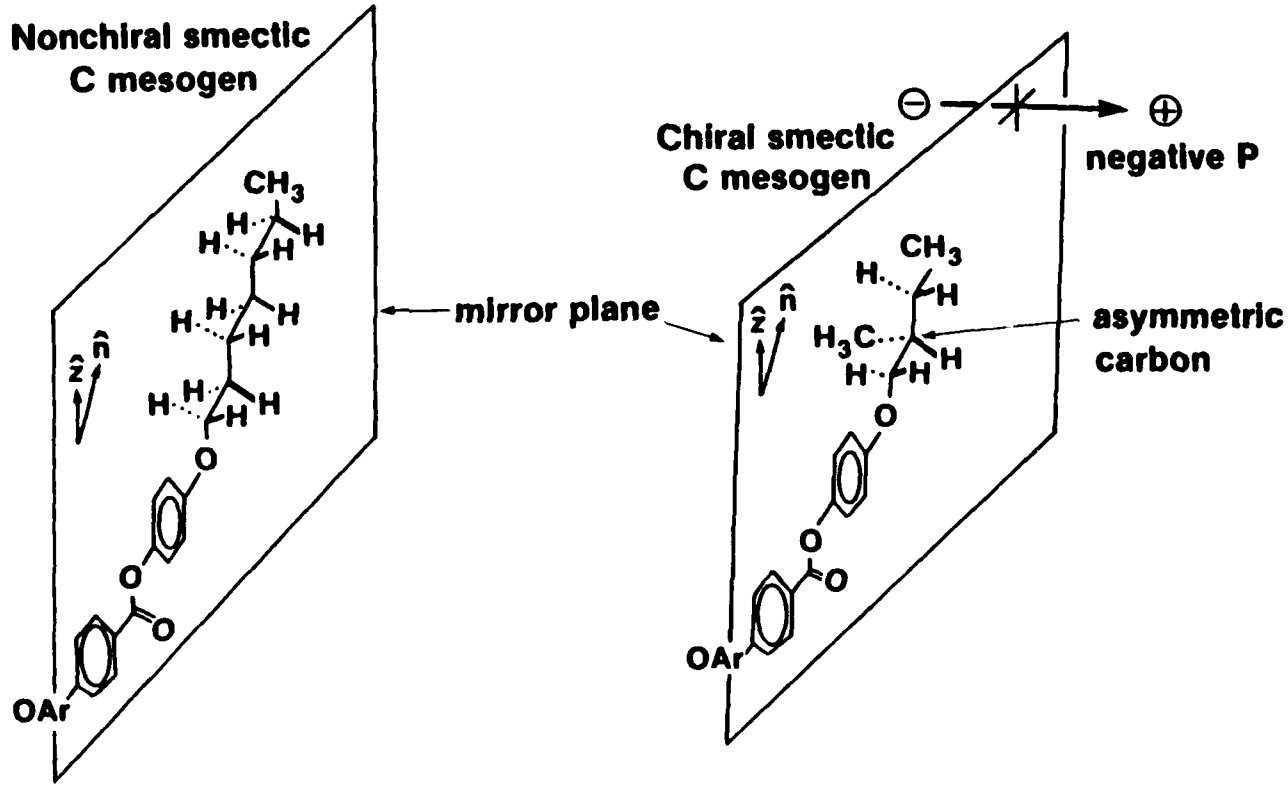


(d)

G1960

Chiral Centers Cause Spontaneous Formation of Permanent Dipoles by Reducing Molecular Symmetry

UR
LLE

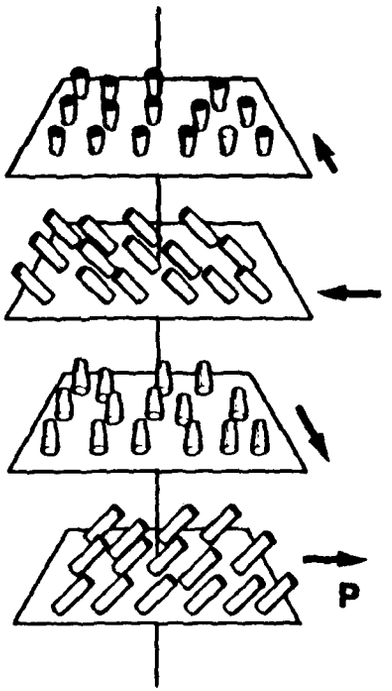


Walba *et al.*, *J. Am. Chem. Soc.* 108, 5217 (1986).

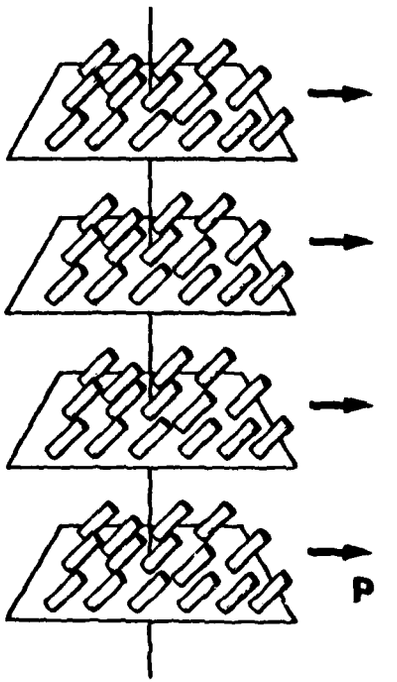
G1929

Chiral Smectic Liquid Crystals Must be Untwisted to Show Ferroelectric Properties

UR LLE



(a) twisted structure
net average dipole moment = 0
no bulk ferroelectric properties.



(b) untwisted structure
nonzero average dipole
ferroelectric properties exhibited.

G1932

Methods of Untwisting the Chiral Smectic Helix

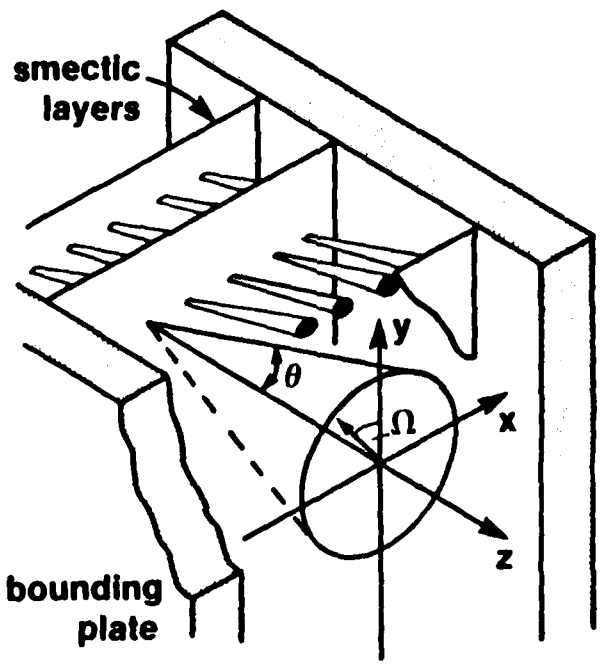
UR LLE

- Electric-field unwinding
- Magnetic-field unwinding
- Mixing of materials with opposite chirality
- Unwinding by surface forces and thin cell spacings

G1933

Elastic Unwinding of the Chiral Smectic C Helix by Surface Forces and Thin Cell Spacing

UR LLE



θ = molecular tilt angle within layer

Ω = angle of tilt of molecule off surface (splay)

M. Handschy, N. Clark, and S. Lagerwall, *Phys. Rev. Lett.* 51, 471-474 (1983).

G1934

Surface-Stabilized, Ferroelectric, Liquid-Crystal Device (SSFLC)

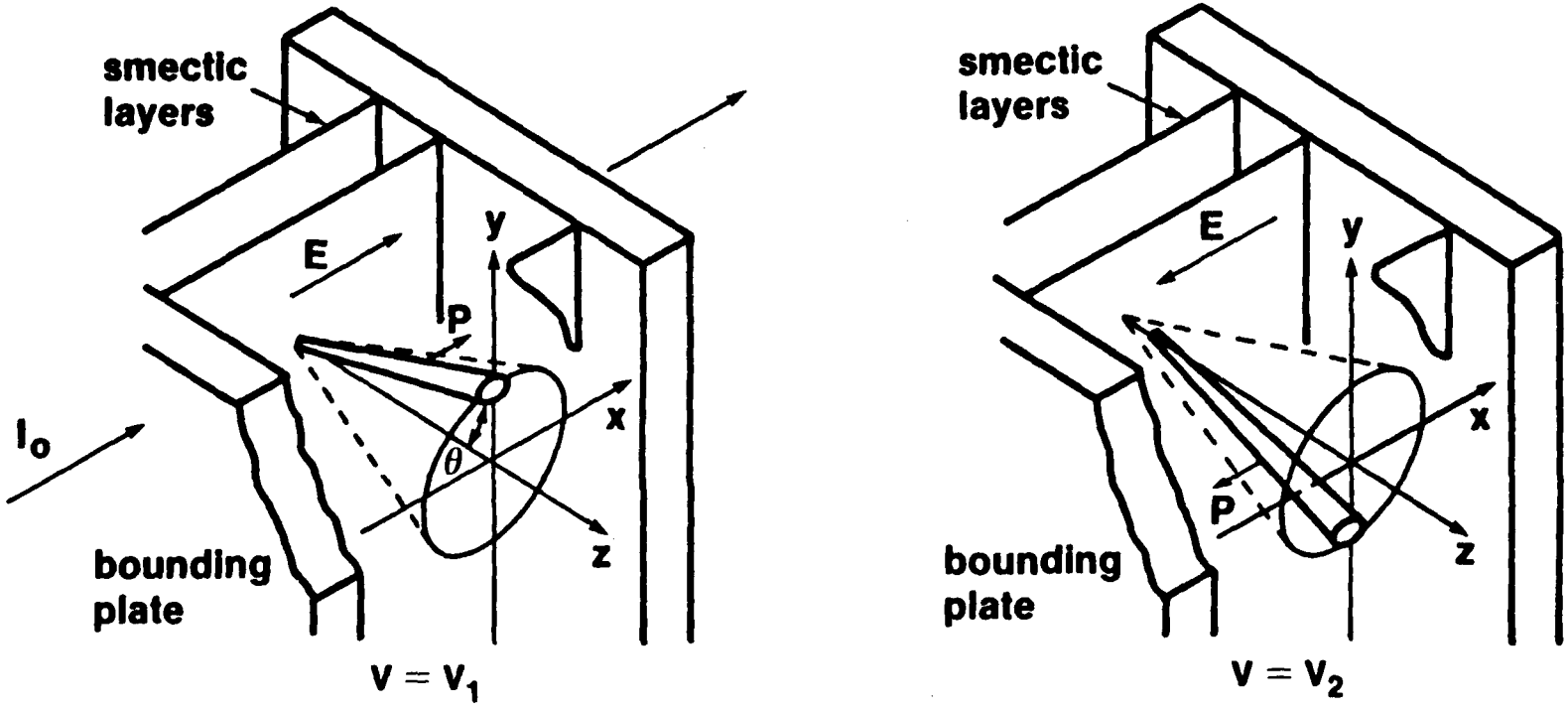
UR LLE

- Cell thickness < pitch, bistable
- Most widely investigated
- Reasons:
  - fast response (0.5 μs demonstrated)
  - bistability; controlled by boundary conditions
  - large electro-optic effect (20°-60° rotation of an uniaxial material with $\Delta n = 0.2$)
  - slow development; lack of materials with room-temperature ferroelectric phases

G1937

Director Reorientation in the SSFLC Device

UR
LLE

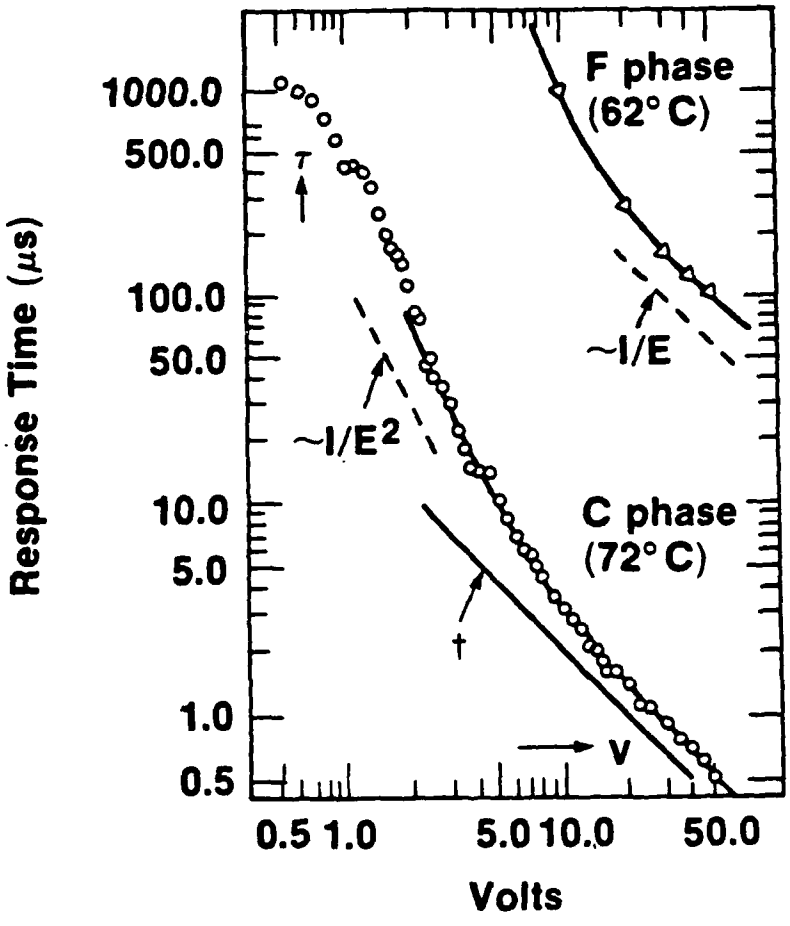


- Angle of deflection = 2θ (θ = molecular tilt angle within smectic layer)
- Typical values for θ are between 22.5° and 45° (material dependent)

G1941

Electro-Optic Response of SSFLC Device (1.5-μm thick) Using HOBACPC

UR LLE



† Calculated value for an infinite pitch ferroelectric C in the high field limit.

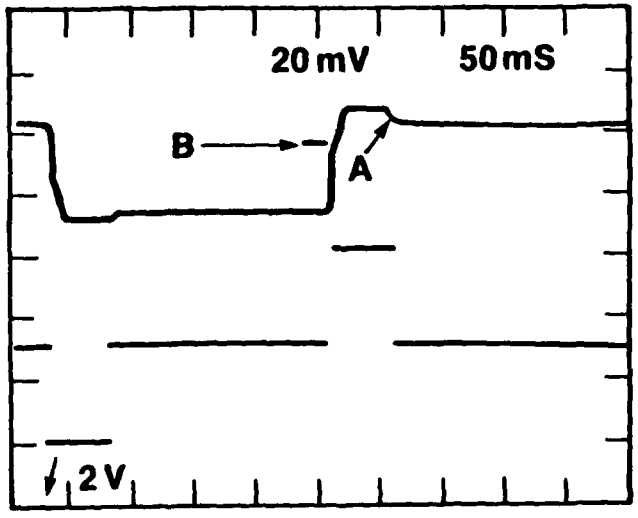
N. Clark and S. Lagerwall, *Recent Developments in Condensed Matter Physics* 4, 317 (1981).

G1938

Bistable Switching in Thin Ferroelectric Liquid-Crystal Cell

UR LLE

cell spacing = 1-2 μm; response time = 1 ms



A = field-off relaxation
B = bulk-surface switching transition

top trace = optical response
bottom trace = 3-V, 5-ms applied pulse

J. Patel, *Appl. Phys. Lett.* 47, 1278 (1985).

G1942

Materials Considerations

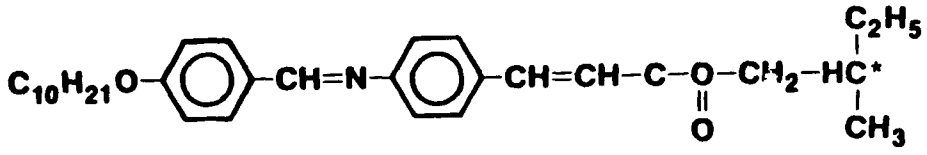
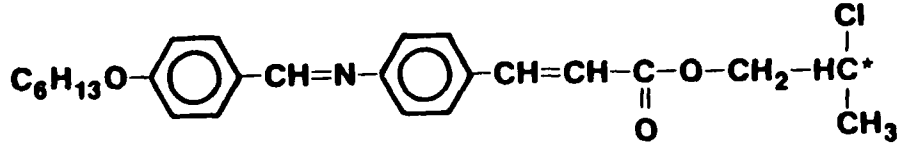
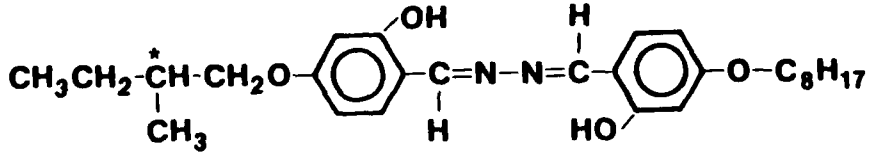
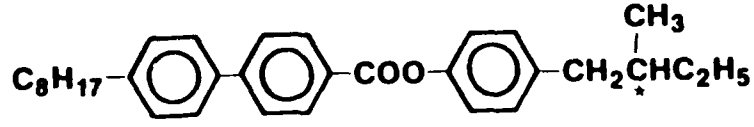
UR LLE

- Desirable properties
  - high chemical stability
  - radiation hardness
  - broad-range ferroelectric phase (room temperature)
  - large spontaneous polarization (low operating voltage)
  - long intrinsic helical pitch (> 5 μm) (fast response)
  - smectic A - chiral smectic C phase transition
- Bulk of investigations employed DOBAMBC and HOBACPC
  - easy synthesis
  - large spontaneous polarization
  - not suitable for room-temperature devices

G1946

Chiral Smectic C Mesogens

UR LLE

Structure	S_C^* Range
 DOBAMBC	85–90° C
 HOBACPC	62–74° C
 disubstituted benzalazine	100–134° C
 CE-8	70.3–87° C

G1947

Recent Materials Advances

UR
LLE

- Eutectic mixtures of existing chiral smectic C materials
- Nonchiral smectic C mixtures doped with chiral smectic C additives
- New, more stable chiral smectic C mesogens with ferroelectric phases near room temperature
- Commercial availability of room-temperature chiral smectic C mixtures (June 1986)

G1948

SURVEY OF COMMERCIALLY AVAILABLE CHIRAL SMECTIC C MESOGENS

UR LLE

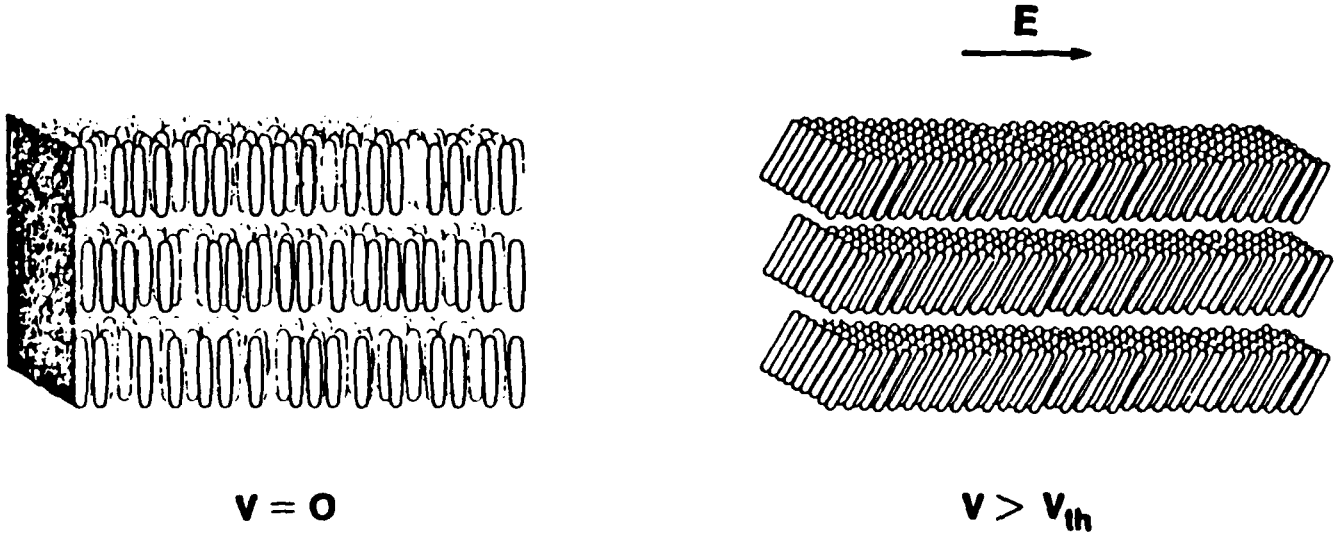
Vendor	Catalog #	Single substance (S) or mixture (M)	Chiral S_c* Range (°C)	Tilt Angle (θ) at 20°C, Degrees	Δn @ 589 nm, 25°C
E. Merck	ZLI-3488	M	-30 to +61	25.5	--
"	ZLI-3489	M	-30 to +65	29.0	--
"	ZLI-3654	M	-30 to +62	25.0	--
"	ZLI-3774	M	-30 to +62	25.5	--
"	ZLI-3775	M	-30 to +61	26.0	--
"	ZLI-4003	M	-20 to +62	23.0	--
BDH	SCE-3	M	0 to +74	25.0	0.17
"	SCE-4	M	0 to +57	23.0	0.17
"	SCE-5	M	-15 to +63	22.5	0.18
"	SCE-6	M	-15 to +63	23.5	0.18
Displaytech	W7	S	+9 to +27	23.0	0.105
"	W81	S	+15 to +56.5	23.0	0.105
"	W37	S	+25 to +37.5	23.0†	0.105
"	W82	S	+30.5 to +70.5	23.0†	0.105
"	W46	S	+64 to +80	23.0†	0.105
"	MDW7	S	+25 to +45.8	23.0†	0.105

† Values estimated from mixture data.

Electroclinic Effect

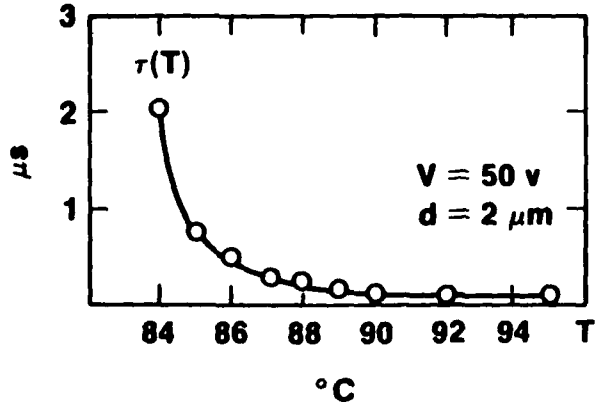
UR LLE

- Garoff and Meyer — 1978[4]
- Coordinated tilt of molecules within layer under influence of an electric field.
- Occurs in smectic A materials containing chiral centers-hindered rotation.
- Response time << Fredericks transition in nematics.

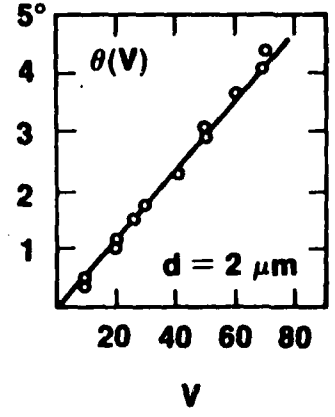


4. S. Garoff and R. B. Meyer, "Electroclinic Effect at the A-C Phase Change in a Chiral Smectic Liquid Crystal," Phys. Rev. A 19, 338 (1979).

Electroclinic ("Soft Mode") Effect - Optical Response



Critical slowing down of switching speed on approaching the A*-C* transition. The material is DOBA-1-MPC, in the A* phase (83°C to 102°C).



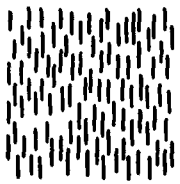
Linearity in the tilt angle response versus applied voltage in DOBA-1-MPC at 86°C.

- Achievable response: < 100 ns with high-temperature compounds
  < 1 μs at room temperature
- Approximately 10–100 times faster than SSFLC mode

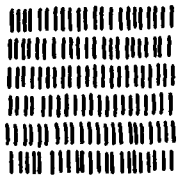
S. T. Lagerwall *et al., Mol. Cryst. Liq. Cryst.* 152, 503-587 (1987).

G2320

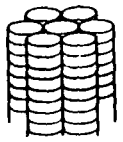
CENTER FOR NIGHT VISION AND ELECTRO-OPTICS
HISTORICAL PERSPECTIVE: LIQUID CRYSTAL RESEARCH AT FORT BELVOIR

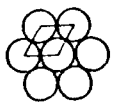


Nematic



Smectic





Discotic

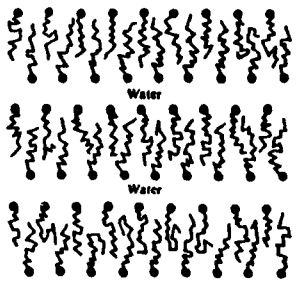


Fig. 1.1.4. The lamellar or neat phase of soaps.

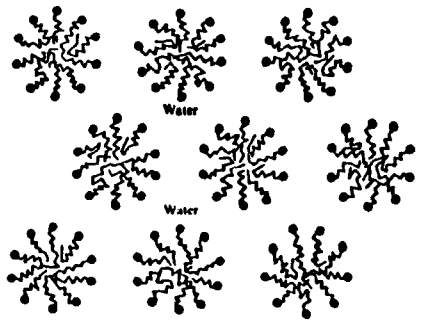


Fig. 1.1.5. The hexagonal or middle phase of soaps.

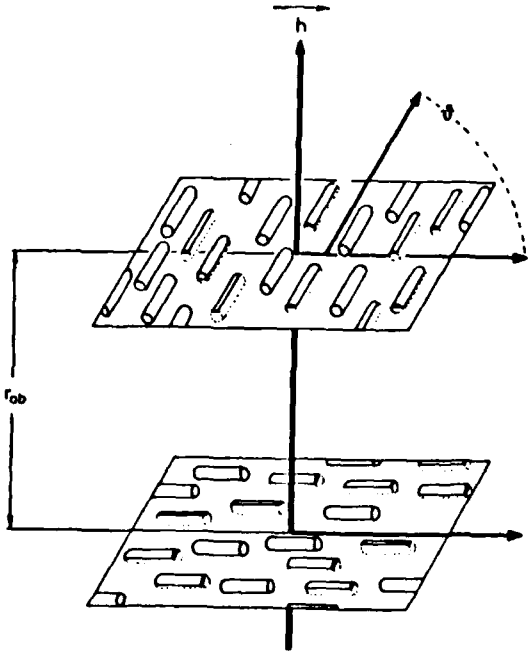


Fig. 21. *Schematic representation of* the cholesteric phase: ϑ = twist angle, $r_{a,b}$ = distance of molecules perpendicular to the director, h = pitch *axis*

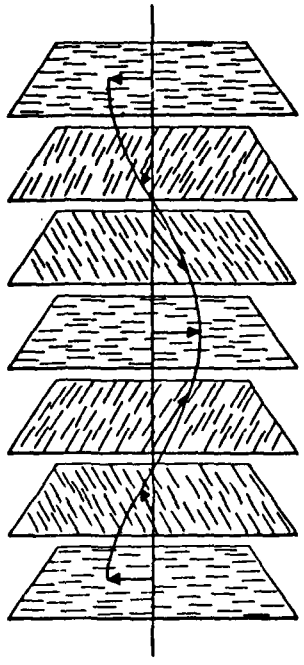
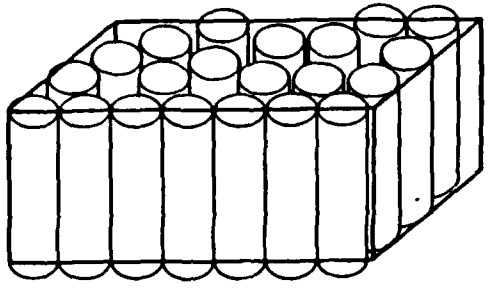
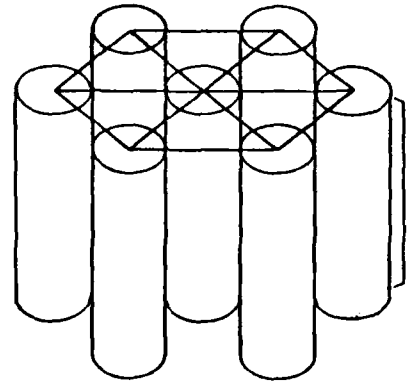


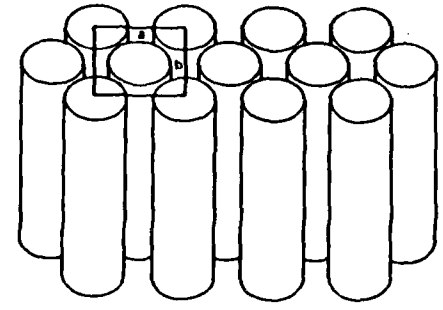
Fig. 1.1.2. The cholesteric liquid crystal: schematic representation of the helical structure.



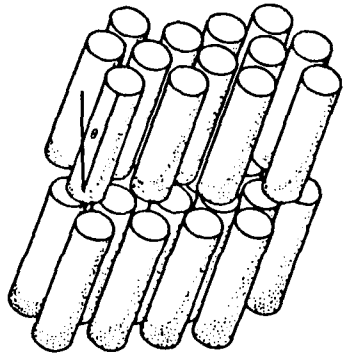
Disordered arrangement of molecular centres in a smectic A phase.



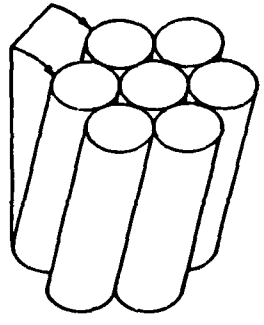
hexagonally close-packed smectic B phase



The packing arrangement of molecules in a layer in the smectic E phase ($b > a$)—see also Fig. 5.1



Structure of the smectic C phase; there is no regular arrangement of the molecular centres in the planes of the unstructured layers. Tilt angles (θ) may range upwards from $\lesssim 10°$.



Hexagonal close-packed molecules in the smectic G phase

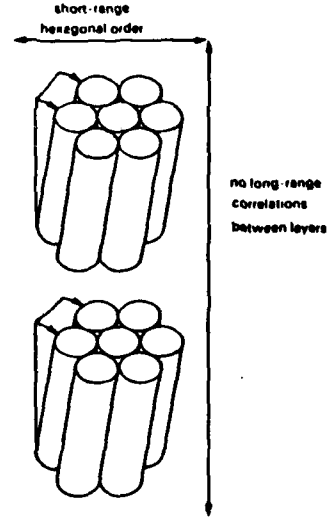


Figure 6.1 Structure of the S_F phase.

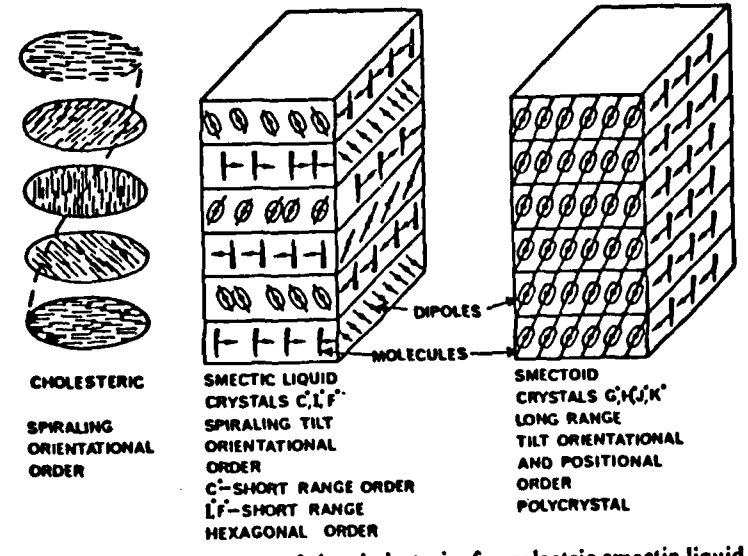


Figure 1. The structures of the cholesteric, ferroelectric smectic liquid crystal, and ferroelectric crystal (smectoid) phases.

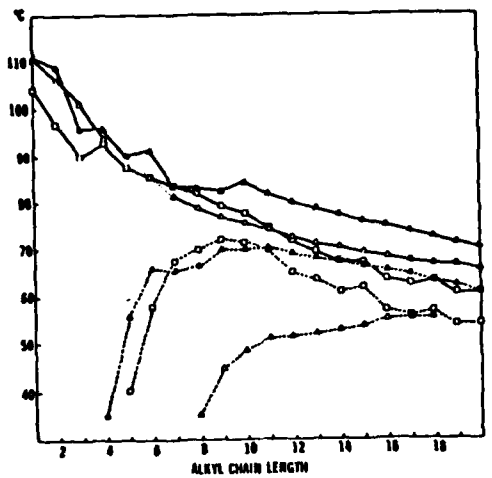


Fig. 19. Transition temperatures of carbonates. Transitions as defined in Fig. 17. Δ, Cholesteryl alkyl carbonates, V; □, cholesteryl *S*-alkyl thiocarbonates, VI; ▲, *S*-cholesteryl alkyl *thiocarbonates*, VII.

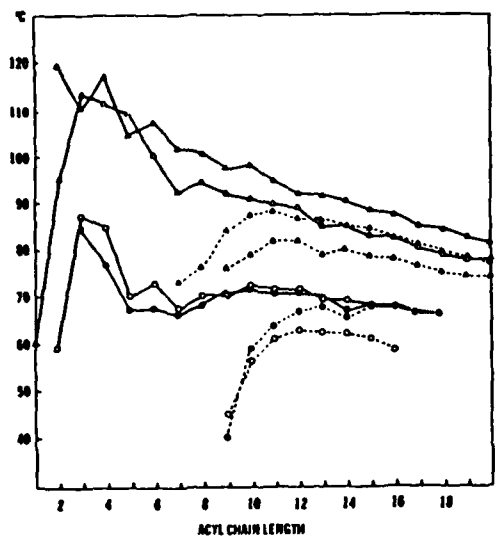


Fig. 17. Transition temperatures of alkanoates. *Solid lines: cholesteric-isotropic* phase transitions; broken lines: smectic-cholesteric phase transitions. Δ, Cholesteryl alkanoates, I; ▲, *S*-cholesteryl alkanethioates, II; O, 5α-cholestan-3β-yl alkanoates, XIV; ●, 5α-cholest-8(14)-en-3β-yl alkanoates, 75.

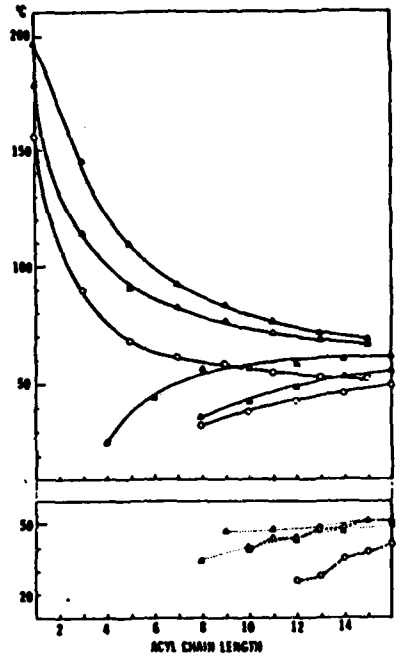
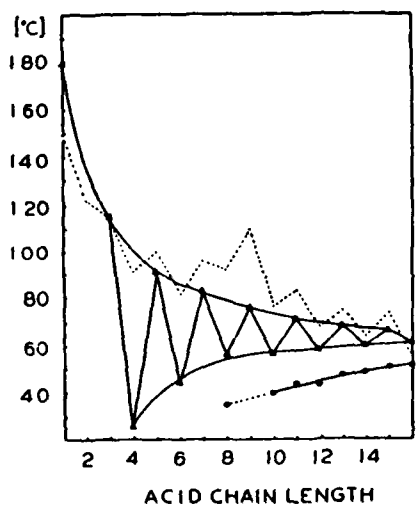
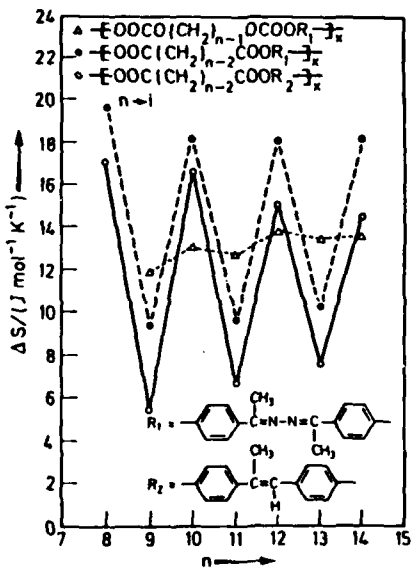


Fig. 18. Transition temperatures of ω-phenylalkanoates. Transitions as defined in Fig. 17. Δ, Cholesteryl ω-phenylalkanoates, III; ▲, *S*-cholesteryl ω-phenylalkanethioates, IV; O, 5α-cholestan-3β-yl ω-phenylalkanoates, XV.





TEMPERATURE INTERVALS OF VISIBLE SPECTRUM OF SELECTIVE REFLECTION [a]

n	I	II	III	IV	V	VI	VII	XIV	XV	XVI	XVII
5	—	—	—	—	—	—	56.3–56.0	—	—	—	—
6	—	—	—	—	—	56.0–53.0	68.5–68.0	—	—	—	—
7	—	72.7–71.5	83.0–82.0	—	—	68.0–67.0	64.3–64.1	—	—	—	34.3–31.3
8	—	74.0–72.9	—	—	41.0–37.3	—	67.3–66.7	—	—	—	47.8–47.0
9	77.9–76.5	—	—	50.3–48.1	50.0–45.5	—	—	—	—	—	52.4–51.9
10	77.1–76.1	—	39.5–39.3	—	51.0–49.4	—	70.2–70.1	—	—	—	55.4–55.2
11	—	—	47.0–44.2	49.9–48.7	52.3–51.5		70.5	61.9–61.1	—	39.5–39.2	—
12	—	—	44.6–44.3	—	53.0–52.1	—	70.5	63.6–63.1	26.6–26.1	43.5–42.1	—
13	—	—	50.0–48.1	51.1–49.8	53.1–52.5	—	68.7	—	—	43.6–42.6	—
14	—	—	48.7–48.3	47.35	53.9–52.9	—	67.8	—	36.0–35.6	—	—
15	—	—	53.0–52.0	52.4–51.6	54.9–54.1	—	66.5	—	—	41.4–40.3	—
16	—	—	51.7–51.3	49.6–49.4	55.7–55.0	—	65.4	—	44.0–41.7	—	—
17	—	—			56.2–55.6	—	64.5	—		—	—
18	—	—			56.4–55.8	57.8–57.4	63.2–63.1	—		—	—
19	—	—			55.1–49.9	—	62.5–62.3	—		—	—
20	—	—			—	57.0–56.0	60.6–60.4	—		—	—

[a] The temperature values were obtained by optical microscopy. n = alkyl or acyl chain length, respectively; for structures see Table II. I, cholesteryl alkanoates; II, *S*-cholesteryl alkanethioates; III, cholesteryl ω-phenylalkanoates; IV, *S*-cholesteryl ω-phenylalkanethioates; V, cholesteryl alkyl carbonates; VI, cholesteryl *S*-alkyl thiocarbonates; VII, *S*-cholesteryl alkyl thiocarbonates; XIV, 5α-cholestan-3β-yl alkanoates; XV, 5α-cholestan-3β-yl ω-phenylalkanoates; XVI, 5α-cholestan-3β-yl alkyl carbonates; XVII, 5α-cholestan-3β-yl *S*-alkyl thiocarbonates.

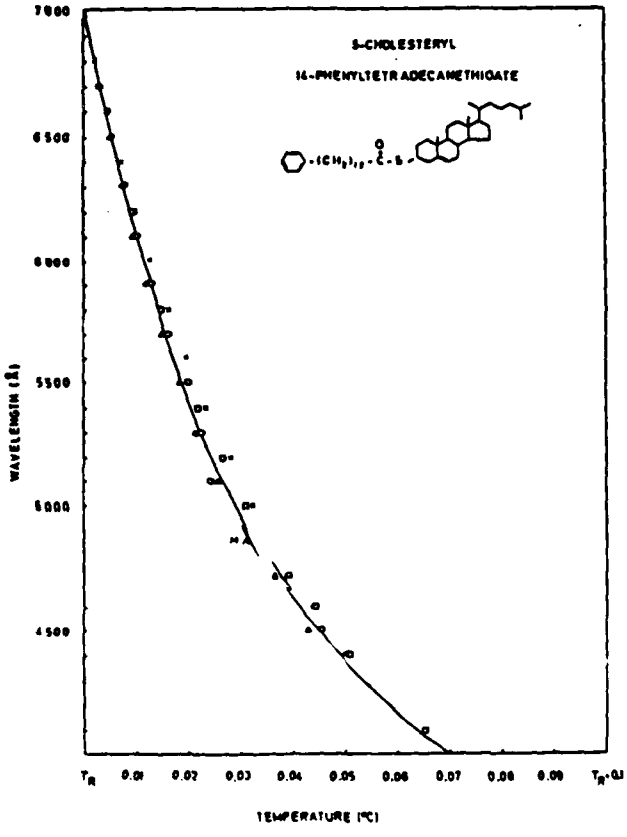


Fig. 23. Wavelength of maximum selective reflection as a function of temperature. Material: *S*-cholesteryl 14-phenyltetradecanethioate. ▲, Data set I; □, data set II, measured on same day on same sample as set I; Δ, data set III, second sample, cooled at 2 m°/min, measured 8 days after set I; ○, data set IV, third sample, cooled at 5 m°/min, measured 9 days after set I (cf. Table IX). [Reproduced from Emulat *et al.*, *Mol. Cryst. Liquid Cryst.* 26, 245 (1974), with permission.]

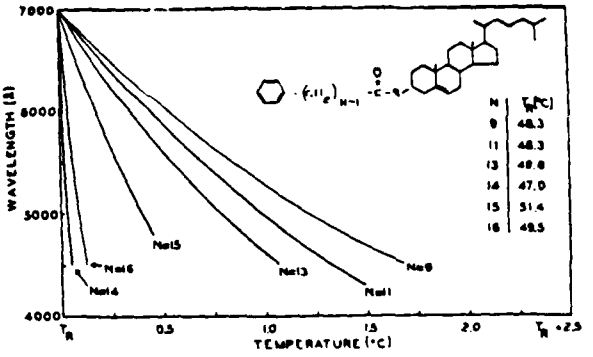


Fig. 24. Wavelength of maximum selective reflection as a function of temperature. Materials: *S*-cholesteryl ω-phenylalkanethioates.

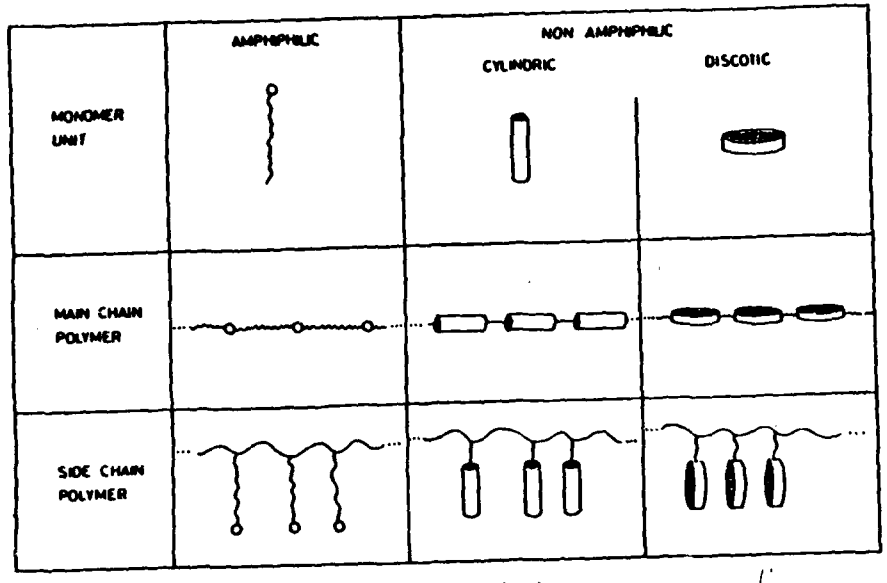


Fig. 1. Classification of liquid crystalline monomers and polymers

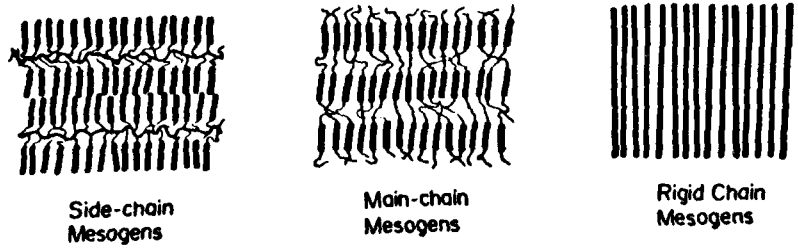


Fig. 13. Schematic representation of macromolecular liquid crystals. A smectic structure is assumed for all cases

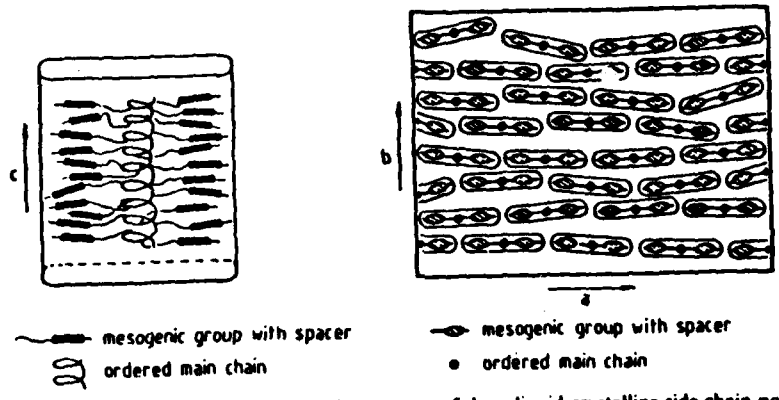


Fig. 31. Schematic model of the smectic structure of these liquid crystalline side chain polymers

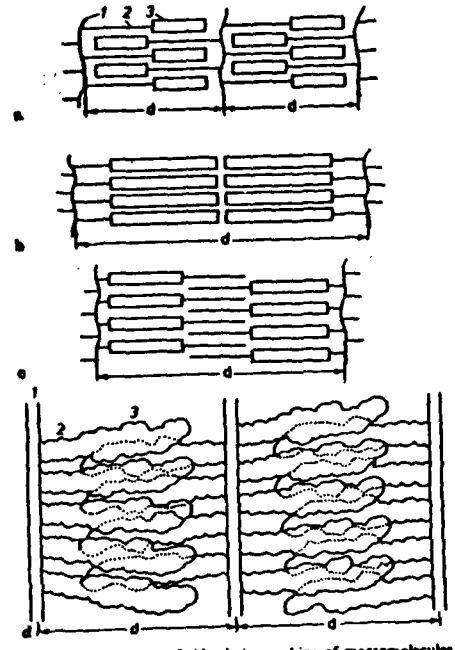


Fig. 10a–d. Schemes of side chains packing of macromolecules in S_A-mesophase of orientated LC polymers; (a) one-layer packing; (b) two-layer packing; (c) packing with overlapping of alkyl "tails"; (d) packing with partial overlapping of mesogenic fragments (side chains are designated by van-der-Waals radii): 1 — main chain; 2 — spacer; 3 — mesogenic group (Side groups of neighbouring macromocules (in the cases a, c and d) are arranged in different planes parallel to the plane of the figure)

WES

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CURRENT LIQUID CRYSTAL RESEARCH SPONSORED BY NVEOC

Liquid Crystals in R&D Tasks

solicited by Naval Air Development Center under RFP N62269-87-R-0218

Tri-Service Contracts awarded to be awarded

- The University of Rochester
  Institute of Optics / Laboratory for Laser Energetics
  K. L. Marshall, S. D. Jacobs, and coworkers

- Optical Shields, Ltd.
  J. L. Fergason and coworkers

- Hughes Research Laboratories
  S. T. Wu and coworkers

- Honeywell
  Physical Sciences Center
  S. Jenekhe and coworkers

Liquid Crystals in R&D Tasks

to be awarded under BAA issued by DARPA / Army / CNVEO

- Kent State University
  Liquid Crystal Institute
  M. A. Lee, J. W. Doane, and coworkers

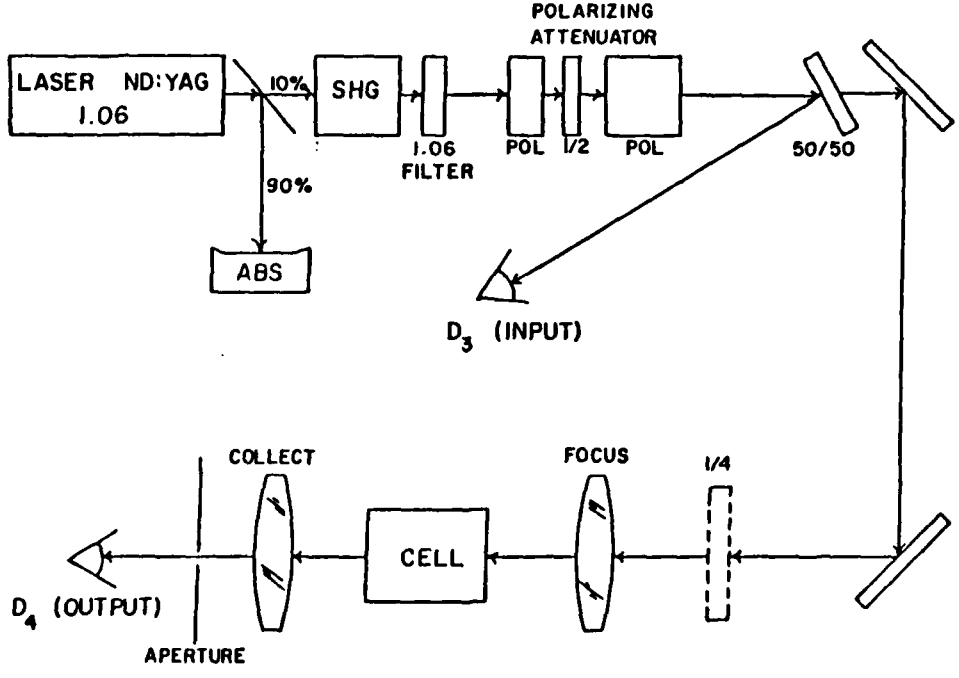
- The Pennsylvania State University
  College of Engineering
  I. C. Khoo

- Optical Shields, Ltd.
  J. L. Fergason and coworkers

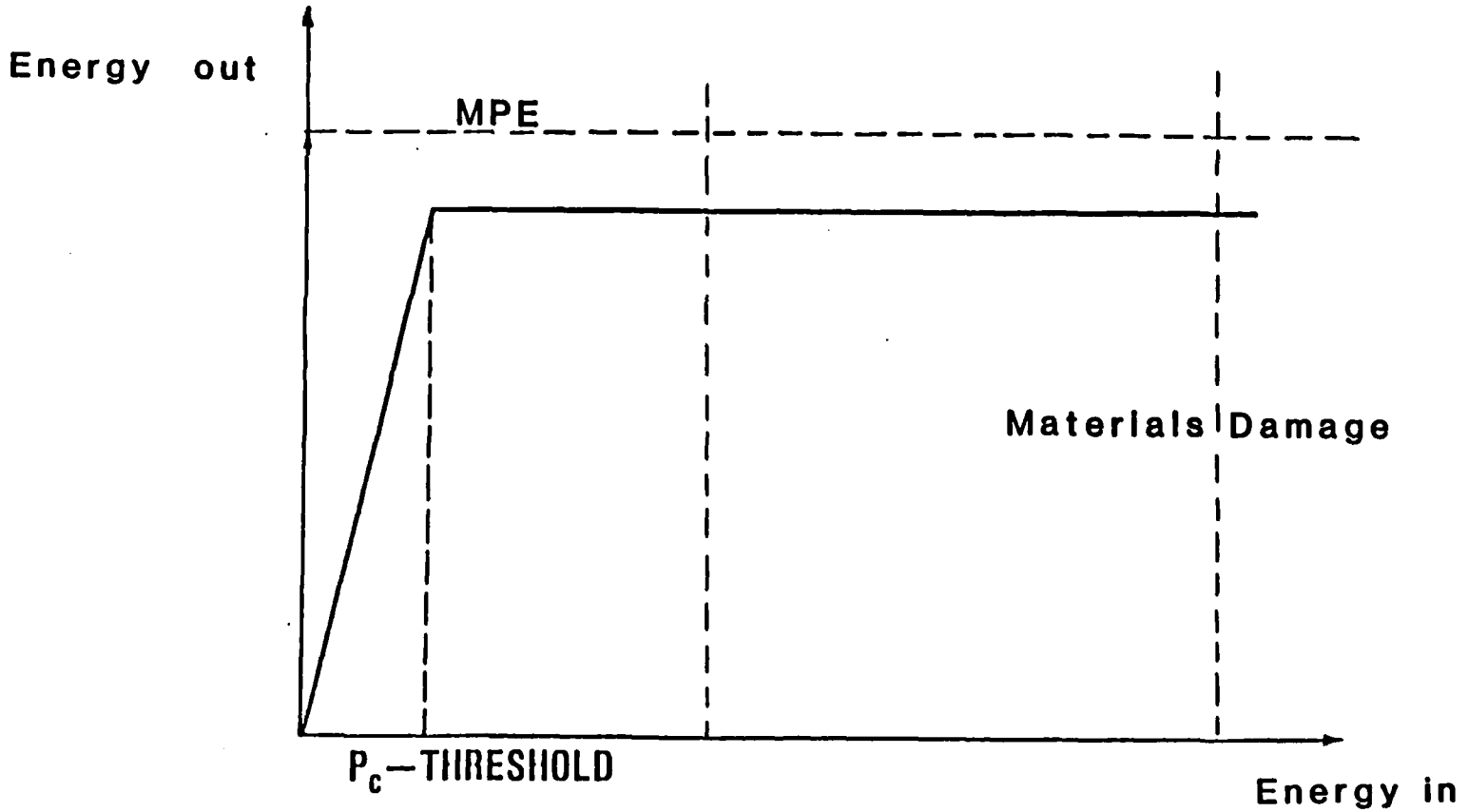
- Honeywell
  Systems and Research Center
  S. K. Lo and coworkers

Nonlinear Measurements

- The University of Central Florida
  Center for Research in Electro-Optics and Lasers
  M. J. Soileau, E. W. Van Stryland, and coworkers

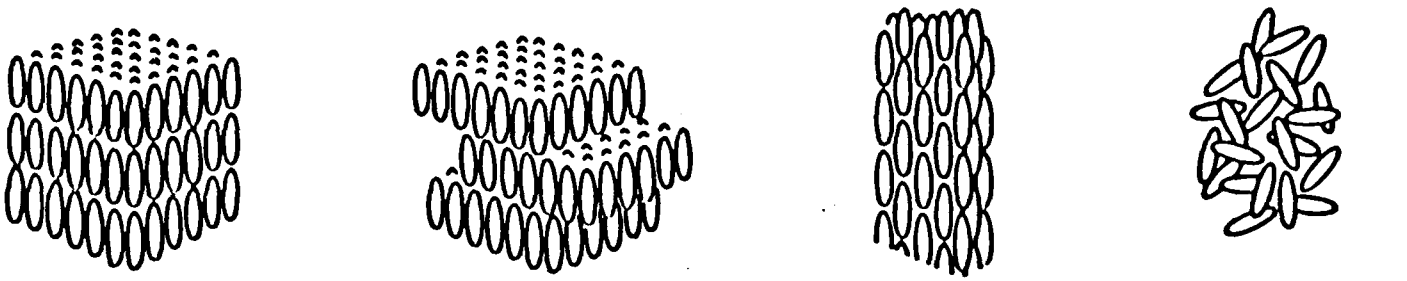


Power/Energy Limiter, ideal



PHASES OF MATERIAL

Liquid Crystal Phase

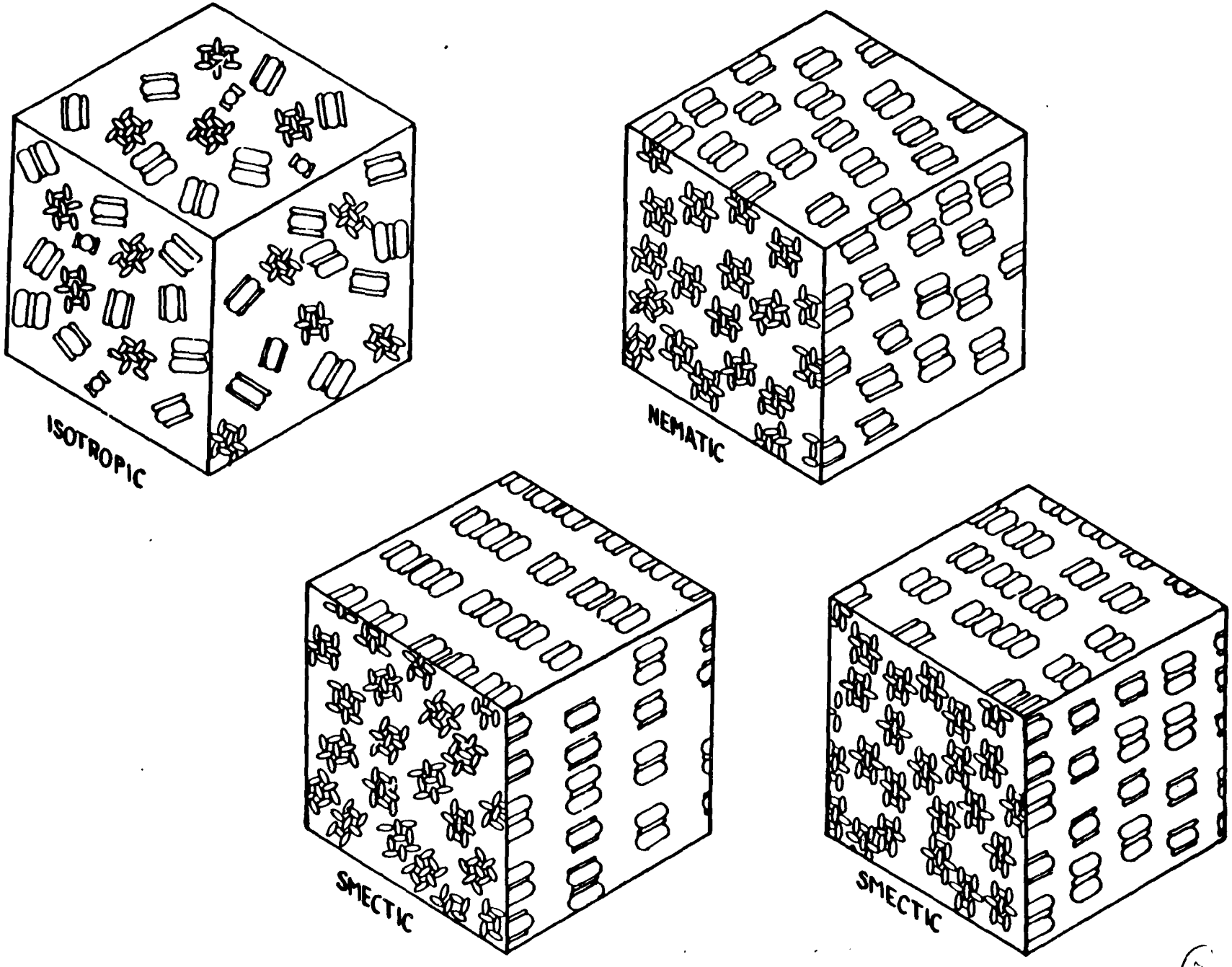


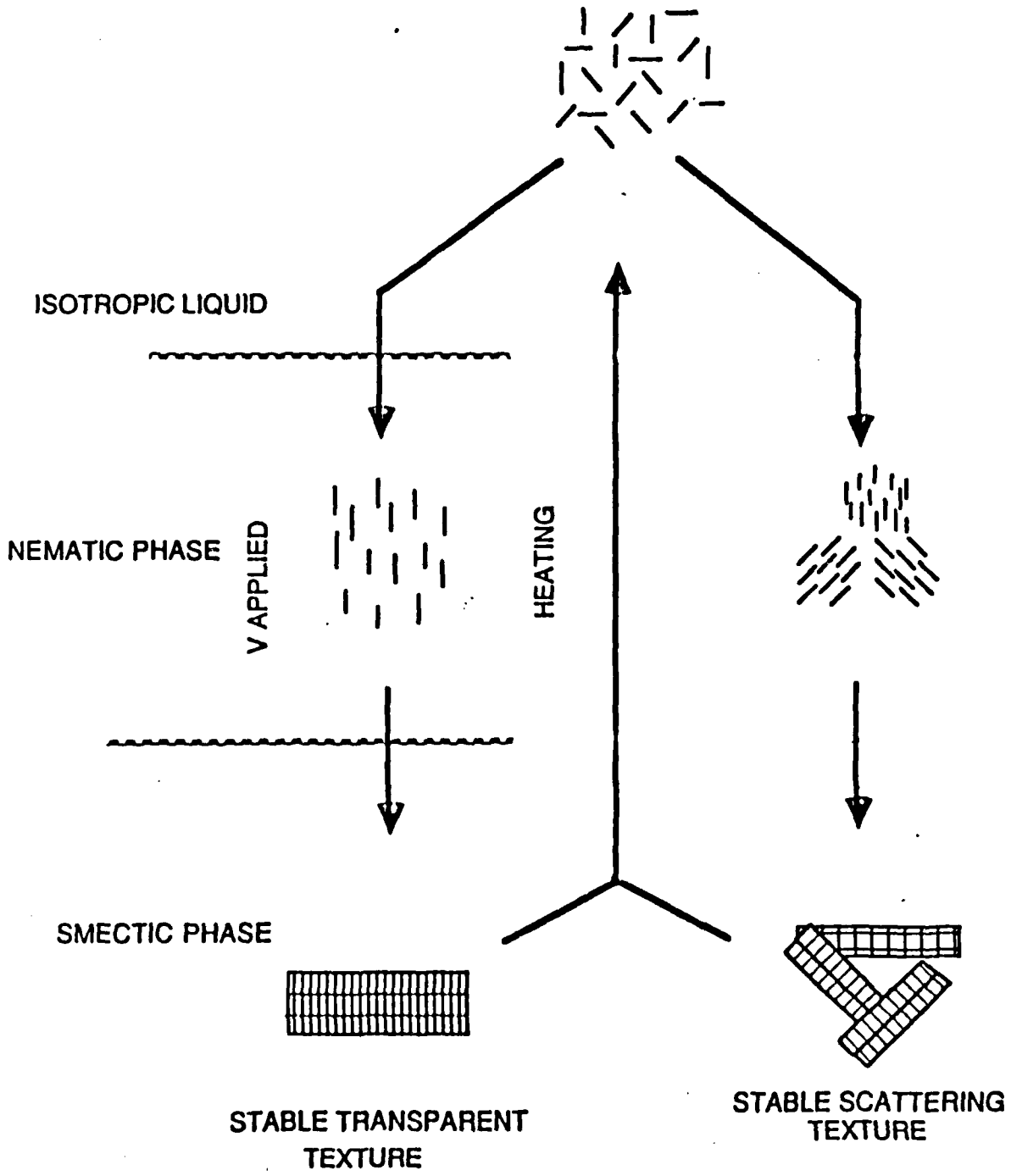
Solid | Smectic | Nematic | Isotropic Liquid

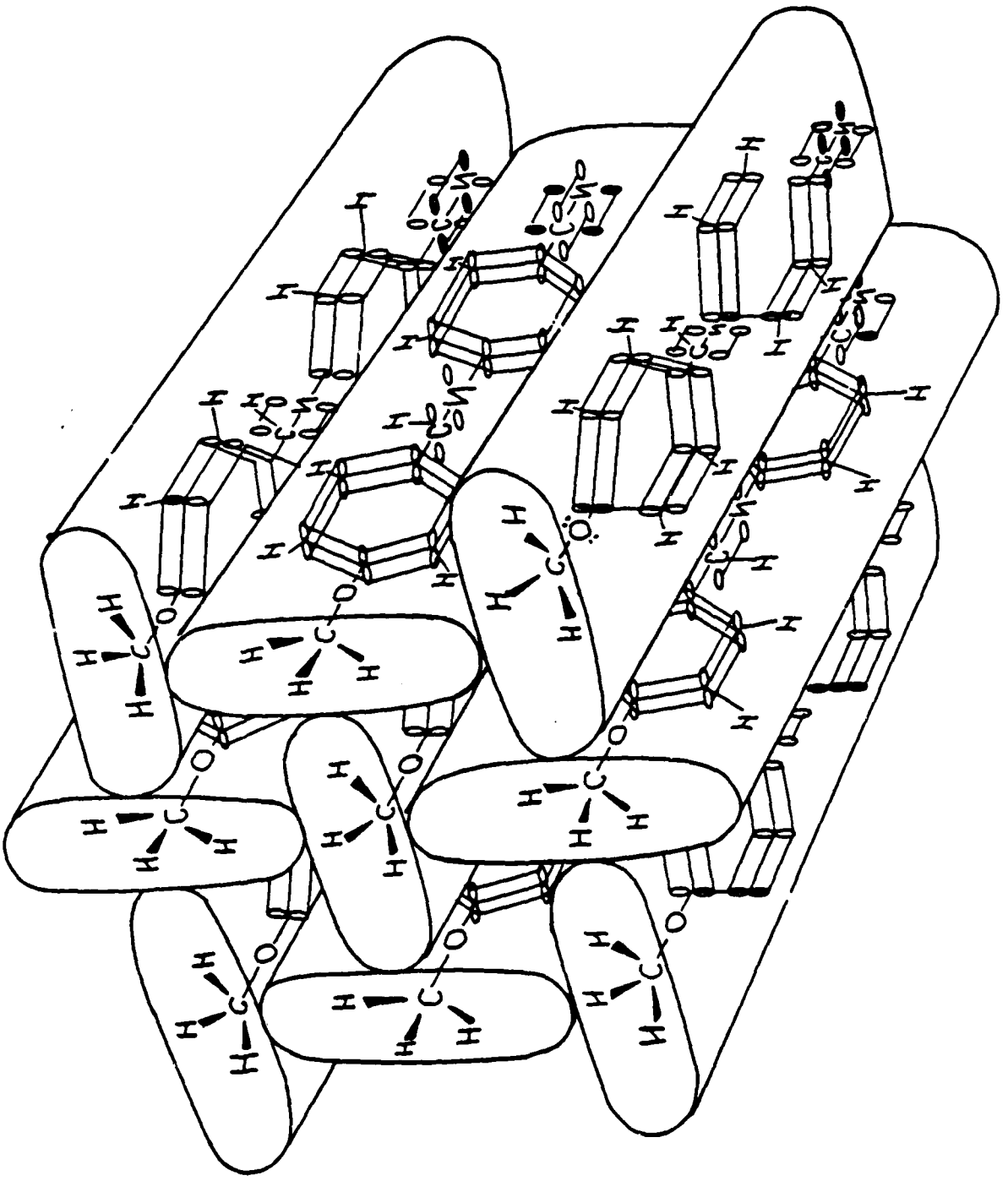
LOW → TEMPERATURE → HIGH

NEMATIC: Orientation Order

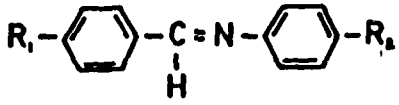
SMECTIC: Orientation & Layer Order


ISOTROPIC
NEMATIC
SMECTIC
SMECTIC


ISOTROPIC LIQUID
NEMATIC PHASE
V APPLIED
HEATING
SMECTIC PHASE
STABLE TRANSPARENT TEXTURE
STABLE SCATTERING TEXTURE



Nonlinear Studies of Schiff Bases

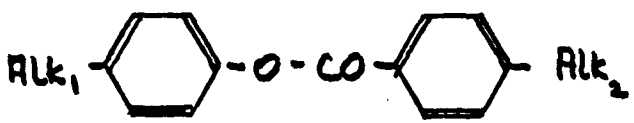


Sample	Color	R_1	R_2	P_c(kW) at 532 nm	(cm/GW) at 532 nm	$n_2 \times 10^{13}$(esu) at 1064 nm
MEBBA	Orange	CH_3	C_4H_9	7±1	.55±.05	6±1
ETBBA	Light Yellow	C_2H_5	C_4H_9	8±1	.5 ±.05	17±2
IPBBA	Light Yellow	C_3H_7	C_4H_9	8±1	.5 ±.05	13±2
BBIPA	Orange	C_4H_9	C_3H_7	7±1	.5 ±.05	12±2
PEBBA	Orange	C_6H_{11}	C_4H_9	7±1	.55±.05	14±2
CS_2	Clear			8±1	Small	130

Mol. Cryst. Liq. Cryst. 127, 321 (1985)

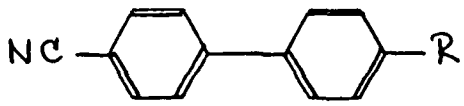
(79

SUBSTITUTED PHENYL BENZOATES

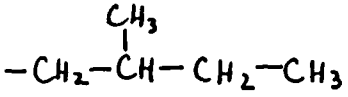


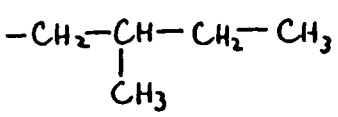
Alk_1	Alk_2	
Bu	Bu	BuPBuB
Bu	Pe	BuPPeB
Pe	Bu	PePBuB
Pe	Pe	PePPeB
i-Pr	Bu	iPrPBuB
Bu	i-Pr	BuPiPrB

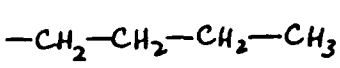
CYANO BIPHENYL DERIVATIVES

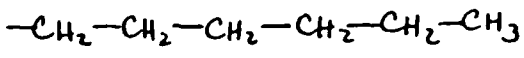


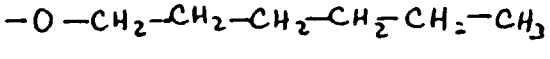
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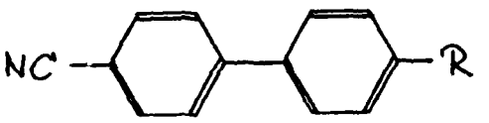


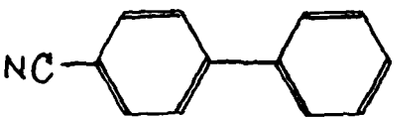


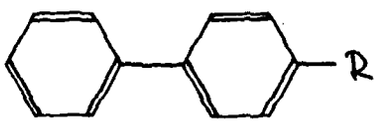


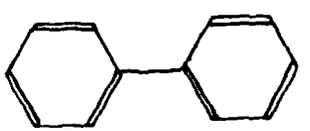


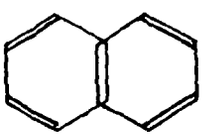
PRECURSORS AND ANALOGUES

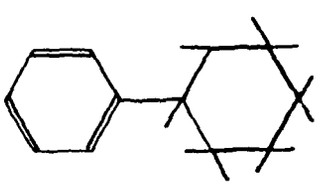


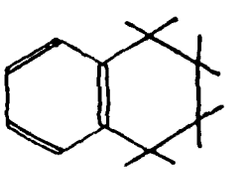












CENTER FOR NIGHT VISION AND ELECTRO-OPTICS
LIQUID CRYSTAL ELECTRO-OPTIC SHUTTER

LIQUID CRYSTAL E-O SHUTTER

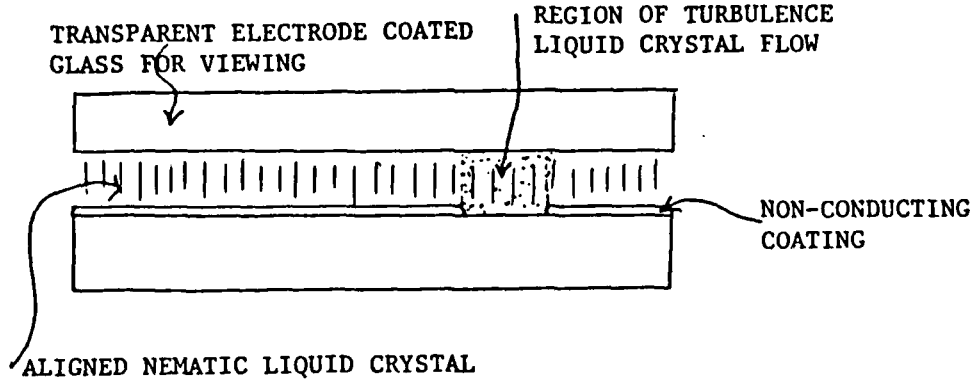
- BACKGROUND
  - NEED FOR CHOPPER
  - PRESENT SOLUTIONS
    - METAL TOOTH WHEEL: ON/OFF
    - GERMANIUM SPIRAL: FOCUS/DEFOCUS
    - DISADVANTAGES
- PROPOSED SOLUTION
  - LINE SCAN CHOPPER
    - DESIRED FEATURES
    - PRINCIPLE OF OPERATION
  - PROGRESS: DR I. C. KOO, PENN. STATE
- CONCLUSIONS
  - PROBLEMS
  - APPROACHES

LINE SCAN CHOPPER-DESIRED FEATURES

- OPERATES BY FORWARD SCATTERING, NOT TRANSMISSION REDUCTION
- WIDE ACCEPTANCE ANGLE: 40° FULL ANGLE
- ELECTRICALLY LINE ADDRESSABLE
- LARGE ARRAY SIZE: 0.5" SQUARE
- LINE WIDTH: <100 MICRON
- LOW INSERTION LOSS: <20%
- BROADBAND OPERATION: 8-12 MICRON
- SWITCHING TIME: <1 ms, ON AND OFF
- FORWARD SCATTERING: >95% INTO ANNULUS 10 LINES DIAMETER
- OPERATING TEMPERATURE: -20°C TO +50°C

PRINCIPLE OF OPERATION

- DYNAMIC SCATTERING IN NEMATIC LIQUID CRYSTAL
- APPLIED E FIELD INDUCES TURBULENT MOTION
- MOTION CAUSES OPTICAL SCATTERING



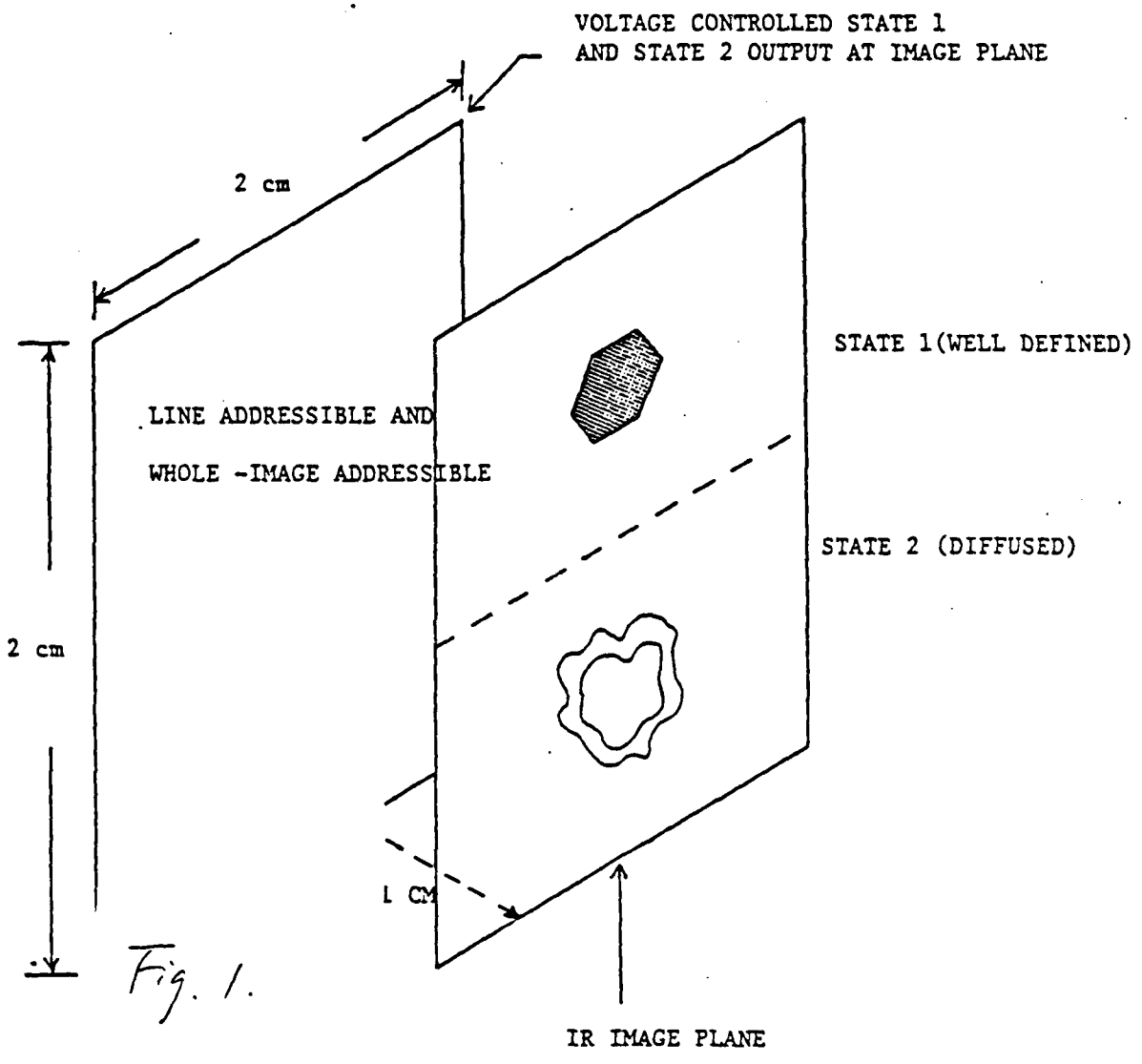


Fig. 1.

L E MODULATOR

LIQUID CRYSTAL CANDIDATES

- NEGATIVE ANISOTROPIC DIELECTRIC NEMATICS
  - E-7, ZLI-1132, NP-5: HIGH $\triangle n$, POSITIVE $\triangle \epsilon$
  - ZLI-3381, ZLI-2806: LOW $\triangle n$, NEGATIVE $\triangle \epsilon$
- CHOSE MIXTURE OF E-7 AND ZLI-3381
  - CHARACTERIZE IR BEHAVIOR
  - USE IN TEST CELL

EM INDUSTRIES

ASSOCIATE OF E.MERCK DARMSTADT WEST GERMANY

ADVANCED CHEMICALS DIVISION

ZLI-3381

PRELIMINARY DATA SHEET

ALTERNATIVE TO ZLI-2585 AND ZLI-2806

PROPERTIES:

S - N		<-30	°C
CLEARING POINT		84	°C
VISCOSITY	20 °C	51	$mm^2 s^{-1}$
	0 °C	175	$mm^2 s^{-1}$
	-20 °C	977	$mm^2 s^{-1}$
	-30 °C	3000	$mm^2 s^{-1}$
	-40 °C	-	$mm^2 s^{-1}$
DIELECTRIC ANISOTROPY (20 °C, 1kHz)	$\Delta\varepsilon$	-4.6	
	$\varepsilon_{\parallel}$	3.5	
	$\varepsilon_{\perp}$	8.1	
OPTICAL ANISOTROPY (20 °C, 589 nm)	Δn	0.042	
	n_e	1.516	
	n_o	1.474	
THRESHOLD VOLTAGE (V(10, 0, 20))		1.8 (DAP)	V
TEMP.DEPENDENCE (0 - 40 °C)	dV/dT	-	mV/°C
		-	%/°C

11APR86

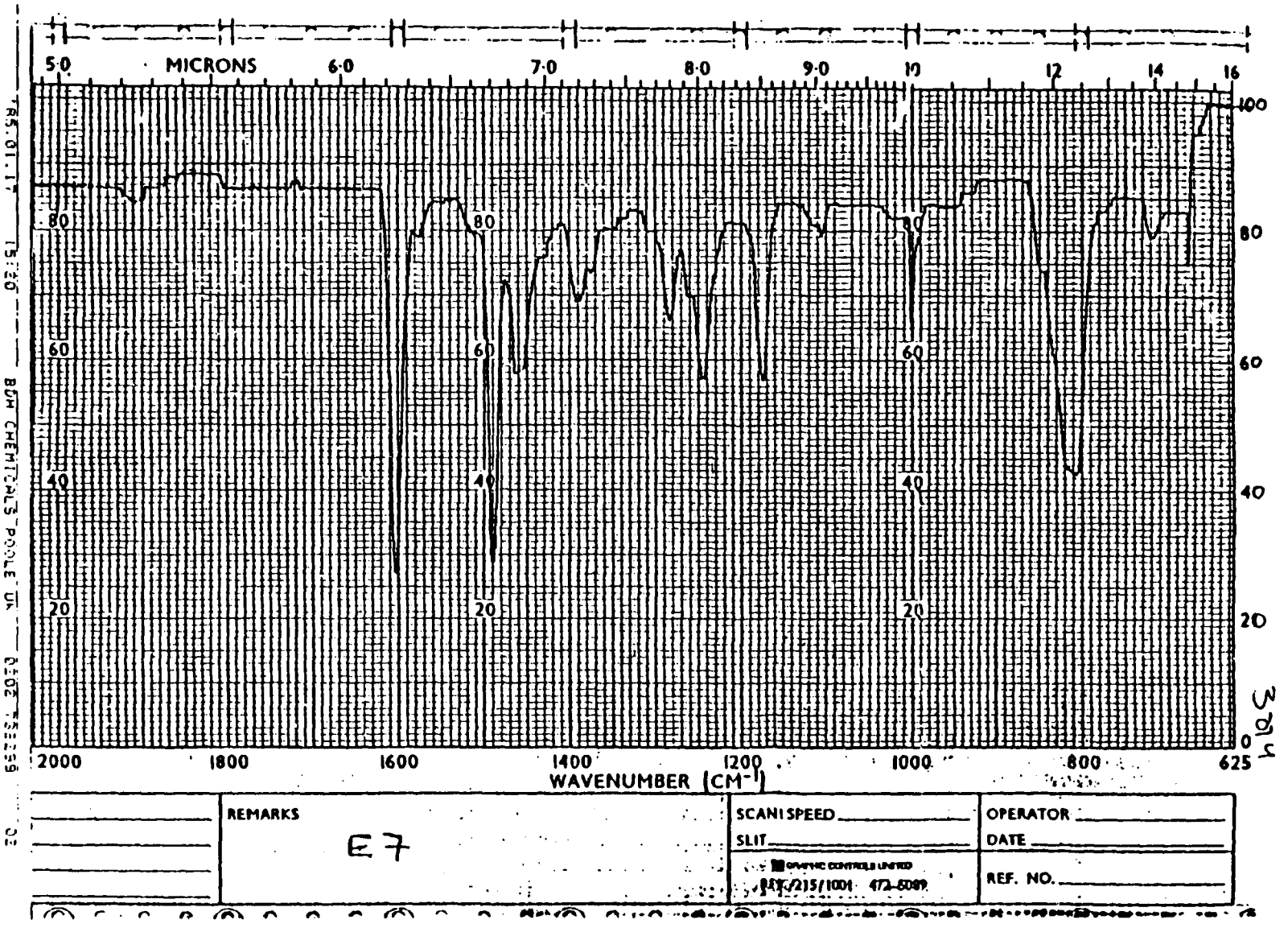
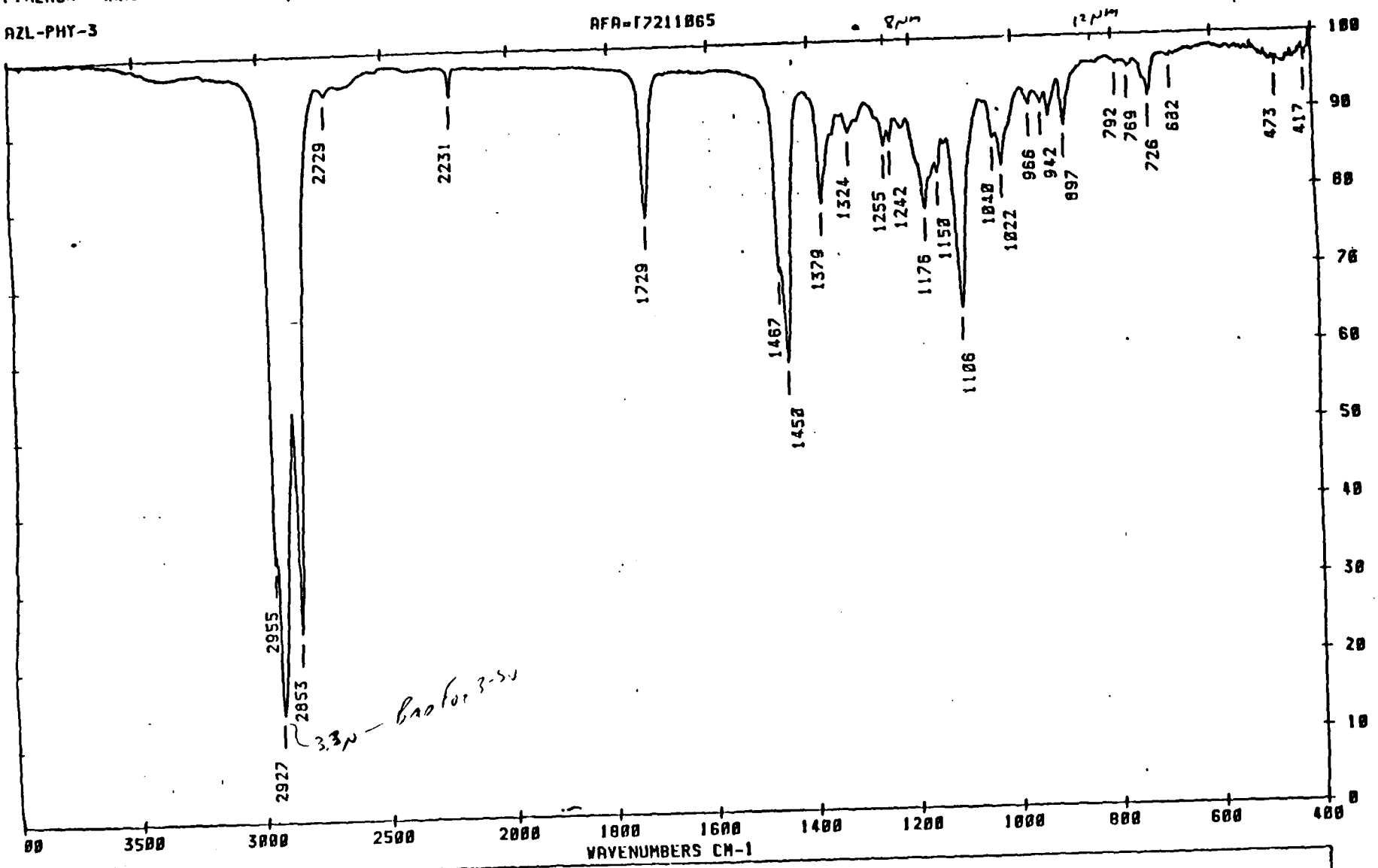

5·0
MICRONS
6·0
7·0
8·0
9·0
10
12
14
16
100
80
60
40
20
0
2000
1800
1600
1400
1200
1000
800
625
WAVENUMBER (CM⁻¹)
REMARKS
E7
SCAN SPEED
SLIT
OPERATOR
DATE
REF. NO.

Fig. 6

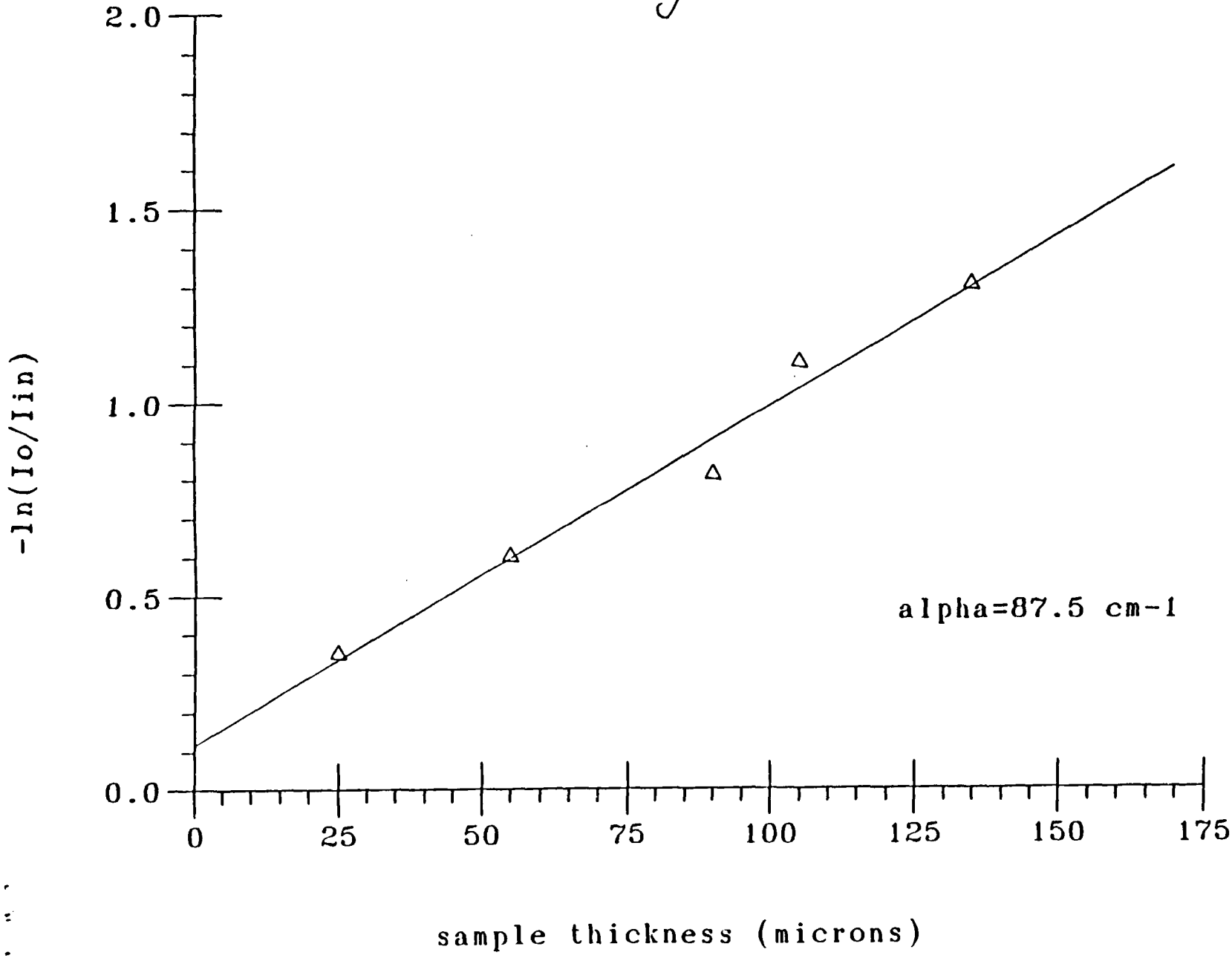


SUBSTANZ: ZLI 3381 Z/312	
HERKUNFT: DR.GOETZMANN	BEMERKUNGEN:
PRAEPARATION: KBR-KAPILLAR	
BEARBEITER: LEHMANN	TIME 12:38:22 DATE 30/09/87 IR.NR.97211065

Fig. 5

EM Chemicals ZLI3381 Absorption Data at 10.6 Microns

Fig. 8



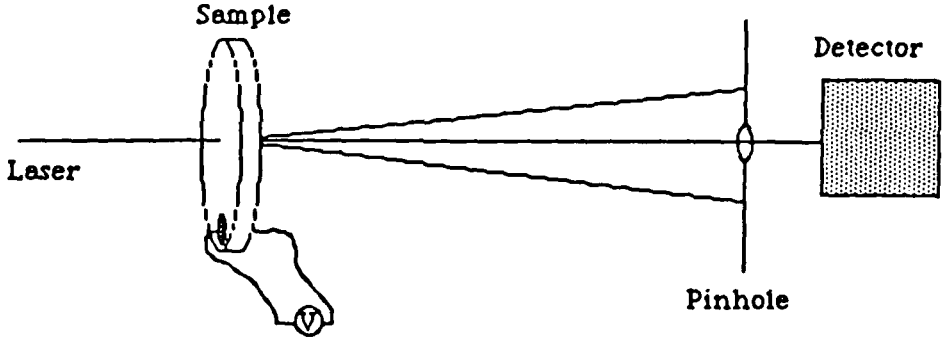
EXPERIMENTAL RESULTS

- CELLS USING Ge AND ZnSe WERE FABRICATED (1" x 1")
- ACCEPTANCE ANGLE LARGE: >40°
- "OPTIMUM" THICKNESS ON ORDER OF 20 μm YIELDS $\approx$ 18% ABSORPTION
- TURBULENCE SIZE DEPENDENCE ON VOLTAGE DETERMINED
- DYNAMIC SCATTERING DEFOCUSING DEMONSTRATED WITH CO_2 LASER
- RESPONSE TIMES MEASURED
  - SCATTERING TURN ON $\approx$ 1 ms
  - SCATTERING TURN OFF $\leq$ 100 ms

TURBULENCE SIZE VOLTAGE DEPENDENCE

	25 µm Sample
Volts	Turbulence size
10	40 µm x 80 µm
13	40 x 60
15	32 x 40
18	24 x 32
20	20 x 20
30	16 x 16
40	8 x 12

DYNAMIC SCATTERING SETUP



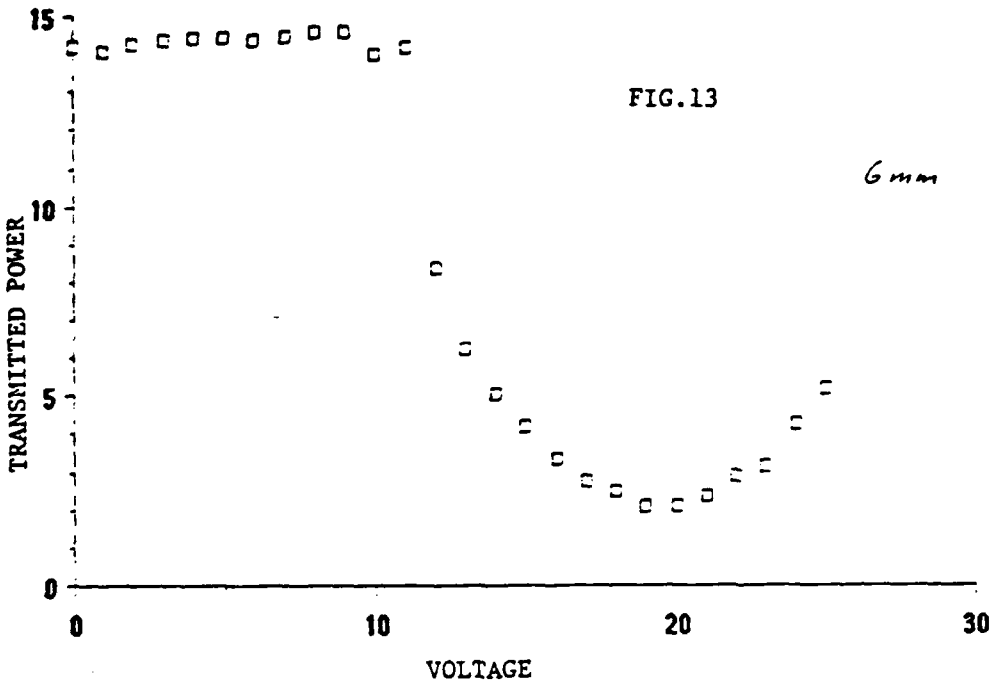

15
10
5
0
TRANSMITTED POWER
0
10
20
30
VOLTAGE
6mm

FIG.13

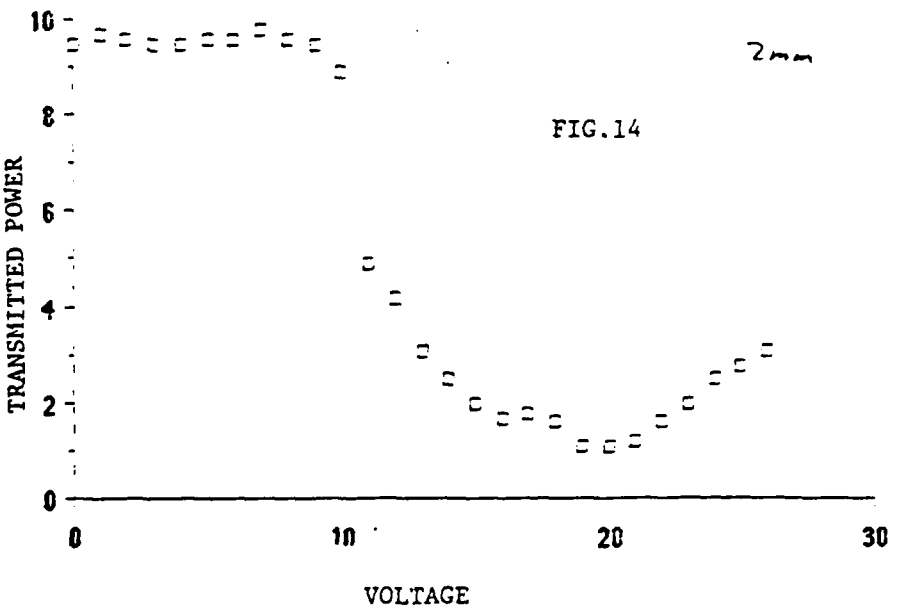

10
8
6
4
2
0
TRANSMITTED POWER
0
10
20
30
VOLTAGE
2mm

FIG.14

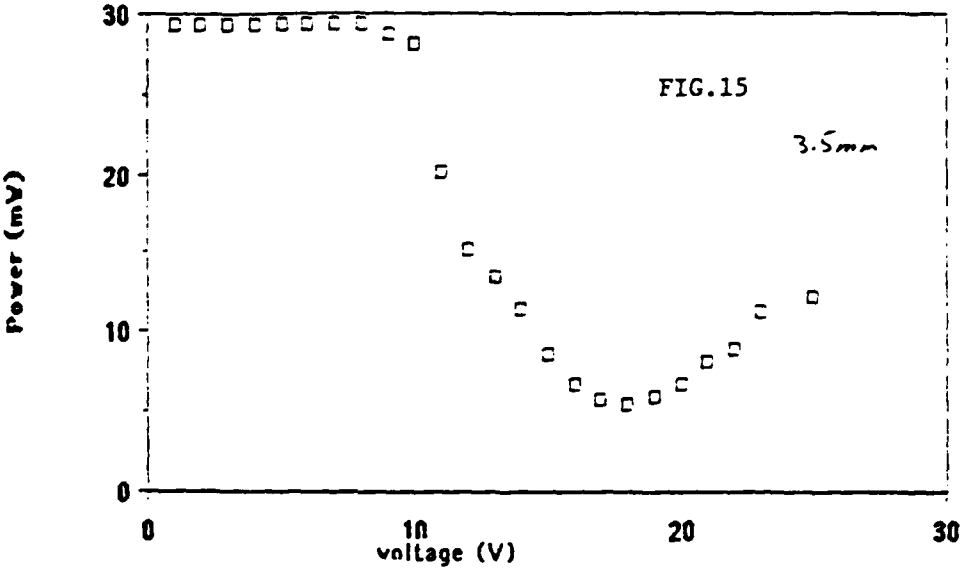

30
20
10
0
Power (mV)
0
10
20
30
voltage (V)
3.5mm

FIG.15

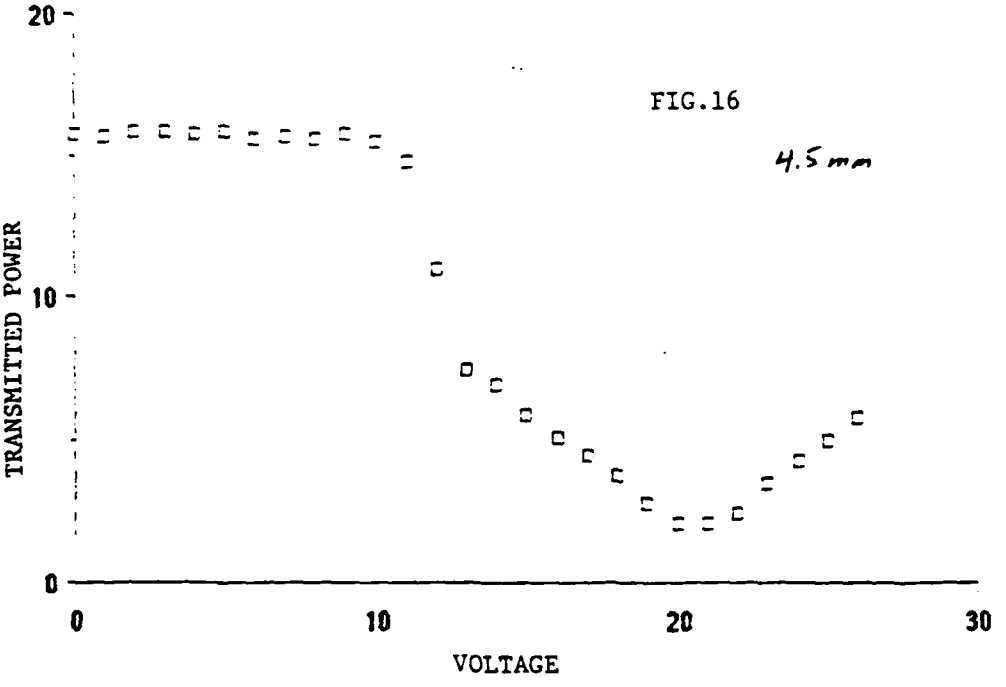
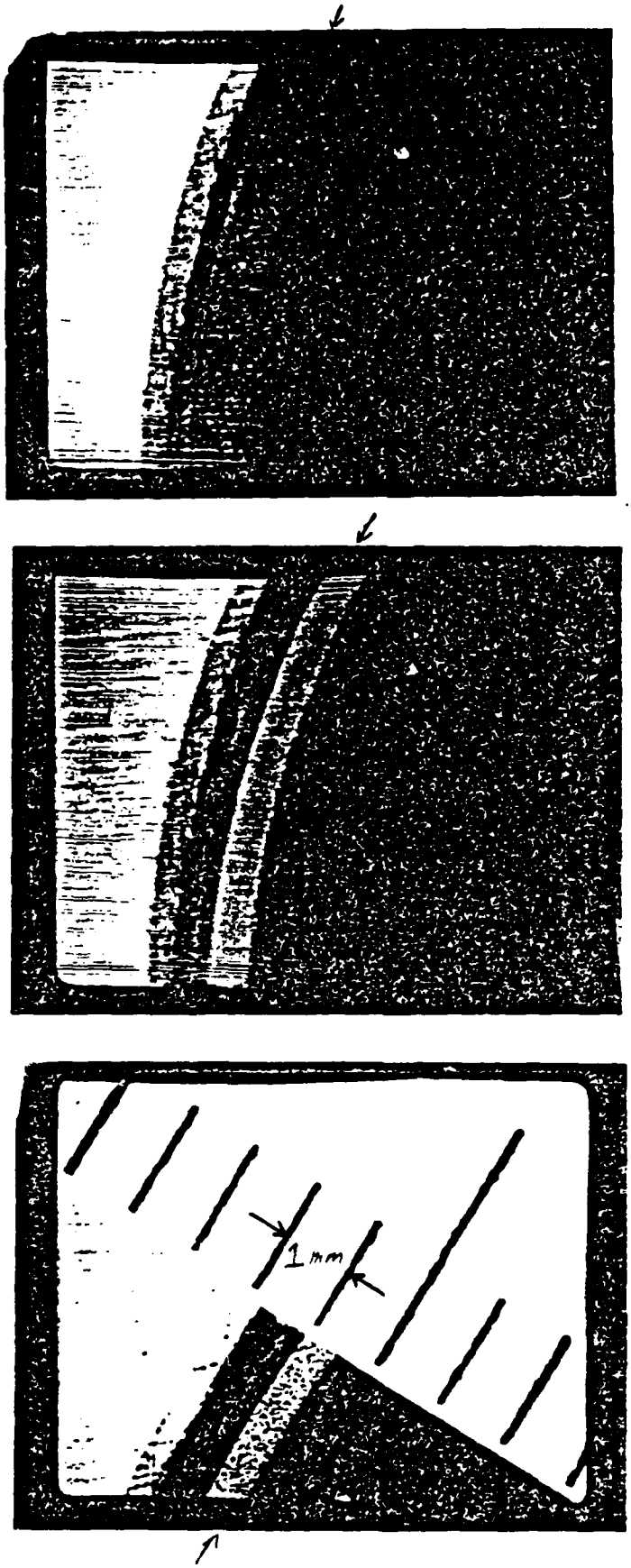

20
10
0
TRANSMITTED POWER
0
10
20
30
VOLTAGE
4.5mm

FIG.16

Figures 18.



A

B

C

CONCLUSIONS

- TURN OFF TOO SLOW: 100 ms → 1 ms
  - SIZE EFFECTS
  - E FIELD EFFECTS
- FIELD CRYSTAL MIXTURE NEEDS OPTIMIZING
- ELECTRODE EFFECTS NEED CHARACTERIZING
- SCATTERING ANGLES NEED CHARACTERIZING
- MULTI-LINE CELL NEEDS DEMONSTRATION
  - INSERTION LOSS
  - IMAGE DEGRADATION
- IN GENERAL, PROMISING APPROACH

WORKSHOP

Liquid Crystals for Laser Applications

Night Vision and Electro-Optics Center
Fort Belvoir, VA

11 May 1988

University of Rochester
Organizer

S. D. Jacobs
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LRT = Laser Research Team
UDDT = Uncoded Devices Development Team